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OPTIMIZATION IN THE DESIGN OF CONCRETE MIXES FOR THE SUSTAINABILITY OF A SOUTH AMERICAN METROPOLITAN AREA BY IMPLEMENTING MATERIAL LIFE CYCLE ANALYSIS

OPTIMIZACIONES EN EL DISEÑO DE MEZCLAS DE CONCRETO PARA LA SOSTENIBILIDAD DE UN ÁREA METROPOLITANA DE SUDAMÉRICA IMPLEMENTANDO ANÁLISIS DE CICLO DE VIDA DE MATERIALES

OTIMIZAÇÕES NO PLANEJAMENTO DE MISTURAS DE CONCRETO PARA A SUSTENTABILIDADE DE UMA ÁREA METROPOLITANA NA AMÉRICA DO SUL, IMPLEMENTANDO A ANÁLISE DO CICLO DE VIDA DOS MATERIAIS

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RESUMEN

El análisis de Ciclo de Vida ACV, es una metodología que identifica los aspectos ambientales y los impactos potenciales asociados con un producto mediante la compilación de un inventario de las entradas y salidas del sistema para su optimización, planificación estratégica e implementación de políticas sostenibles. En el ámbito de la producción de concretos, se han utilizado diversas técnicas de optimización y su impacto en el diseño de mezclas como análisis multicriterio, modelos estadísticos, materiales cementantes suplementarios y algoritmos de optimización. Este trabajo aplica el ACV a la producción de concreto el Área Metropolitana del Valle de Aburrá, Colombia, con la hipótesis de optimizar las proporciones, sin agregar aditivos ni adiciones especiales, se puede reducir las emisiones de CO_2 y el consumo de energía. Utilizando la metodología ACI 211, se diseñaron mezclas de concreto y se evaluaron sus impactos ambientales. Los resultados muestran que el uso de agregados gruesos de mayor tamaño reduce el consumo de cemento, disminuyendo las emisiones de CO_2 hasta un 15%. La mezcla óptima no sólo es más económica, sino también de menor impacto ambiental. Las conclusiones indican que es posible compatibilizar la eficiencia económica, promoviendo la disminución en la huella de carbono.

Palabras clave
análisis de ciclo de vida ACV, sostenibilidad, optimización de agregados, producción de concreto

ABSTRACT

Life Cycle Assessment (LCA) is a methodology that identifies a product's environmental aspects and potential impacts by compiling an inventory of system inputs and outputs for optimization, strategic planning, and implementing sustainable policies. Several optimization techniques and their impact on mix design have been used in concrete production, such as multi-criteria analysis, statistical models, supplementary cementitious materials, and optimization algorithms. This work applies LCA to concrete production in the Metropolitan Area of the Aburrá Valley, Colombia, with the hypothesis that optimizing proportions without adding special additives can reduce CO2 emissions and energy consumption. Concrete mixes were designed using the ACI 211 methodology, and their environmental impacts were evaluated. The results show that using larger coarse aggregates reduces cement consumption, decreasing CO2 emissions by up to 15%. The optimal mix is not only cheaper but also has a lower environmental impact. The conclusions indicate that it is possible to make economic efficiency compatible with promoting a lower carbon footprint.

Keywords
life cycle assessment LCA, sustainability, aggregate optimization, concrete production

RESUMO

A Avaliação do Ciclo de Vida (ACV) é uma metodologia que identifica os aspectos ambientais e os possíveis impactos associados a um produto por meio da compilação de um levantamento das entradas e saídas do sistema para otimização, planejamento estratégico e implementação de políticas sustentáveis. No campo da produção de concreto, várias técnicas de otimização têm sido usadas e seu impacto no projeto de mistura, como análise multicritério, modelagem estatística, materiais cimentícios suplementares e algoritmos de otimização. Este trabalho aplica a ACV à produção de concreto na Área Metropolitana do Vale de Aburrá, na Colômbia, com a hipótese de que a otimização das proporções, sem a adição de aditivos ou aditivos especiais, pode reduzir as emissões de CO2 e o consumo de energia. Usando a metodologia ACI 211, as misturas de concreto foram projetadas e seus impactos ambientais foram avaliados. Os resultados mostram que o uso de agregados grossos maiores reduz o consumo de cimento, reduzindo as emissões de CO2 em até 15%. A mistura ideal não é apenas mais econômica, mas também tem um impacto ambiental menor. As conclusões indicam que é possível compatibilizar a eficiência econômica e, ao mesmo tempo, promover uma redução na pegada de carbono.

Palavras-chave:
análise do ciclo de vida ACV, sustentabilidade, otimização de agregados, produção de concreto

INTRODUCTION

Concrete production is a fundamental part of the industrial construction sector. However, its environmental impact has become an object of increasing concern in a world searching for sustainable practices due to the overexploitation of resources and the damage to multiple ecosystems. Different research projects have shown that concrete is one of the main generators of GHG (Belaïd, 2022a; Das et al., 2023; Mocová et al., 2019; Watari et al., 2023). The global demand for this material has quadrupled in the last three decades, leading to an increase in CO_2 emissions that has exacerbated the shortage of sand and social conflict (Watari et al., 2023). In this context, LCA becomes an essential tool for evaluating and developing criteria that help mitigate the adverse environmental impacts generated by producing concrete mixtures. Although there are challenges and discrepancies in the measurement of the environmental impact of concrete due to the lack of a standardized LCA methodology, the studies provide criteria for making progress in this framework (Jayasuriya et al., 2023). These discrepancies arise from factors such as scope definition, inventory data, impact assessment, and interpretation (Hafez et al., 2019). However, some standards, such as the NTC-ISO 14044 (ICONTEC, 2021), are implemented in some Latin American countries, especially in Colombia. This standard establishes a systematic and holistic approach to evaluating the environmental impacts of processes and products in a structured way.

ISO 14044 defines this process as the collection and evaluation of inputs, outputs, and potential impacts of a production system for a product through its life cycle. This links the LCA with other approaches, such as Lean Construction (Koskela et al., 2019), and opens up the possibilities of understanding and articulation. Table 1 summarizes some contributions aimed at finding implementations based on ISO 14044.

Through their methodological and numerical models, these tools provide crucial elements for the environmental challenges humanity faces (Boccia & Sarnacchiaro, 2018; Crowther & Seifi, 2022). They also serve as a basis for reversing the World Economic Forum's findings on the behavior of many companies and organizations that often underestimate or overlook the environmental risks associated with their value chain and the lack of sustainable criteria in their projects and business activities (WEF, 2020).

In this sense, it is necessary, through ISO 14044 guidelines, to measure the impacts of CO_2 emissions from the traditional processes of the design of concrete mixtures on site that allow identifying

Table 1. LCA analysis models based on NTC-ISO 14044. Source: Preparation by the authors.

Region	Tool	Description
USA	TRACI (Tool for Reduction and Assessment of Chemical and Other Environmental Impacts) (Henderson, Niblick, & Golden, 2021)	This assesses environmental impacts and provides a database of environmental impacts that can be used in life cycle analysis.
	BEES (Building for Environmental and Economic Sustainability) (Kneifel et al., 2019)	This allows AECO actors to select cost-effective and environmentally friendly construction products based on consensus standards.
Spain	UNE-EN 15804:2012+A1:2014	This provides a framework for the product's environmental statement and evaluates its LCA based on buildings.
European Union	PEF (Product Environmental Footprint) (European Commission, 2021)	These evaluate the multi-criteria environmental impact of products and organizations. They follow the principles of ISO 14040 and 14044.
	OEF (Organizational Environmental Footprint) (Damiani et al., 2022)	
	EW-MFA (Material flow account) (Europäische Kommission Statistisches Amt, 2018)	Theoretical and conceptual foundations of the underlying statistical methodology.
Global	SimaPro (Speck et al., 2016)	LCA analysis software. This follows the ISO principles.
	EIO-LCA (Azari, 2019)	This evaluates economic and environmental interconnections on a national or regional scale.
	SFA (Substance Flow Analysis) (Chertow, 2004)	This evaluates the flow of substances in a given area for a given time (usually a year).

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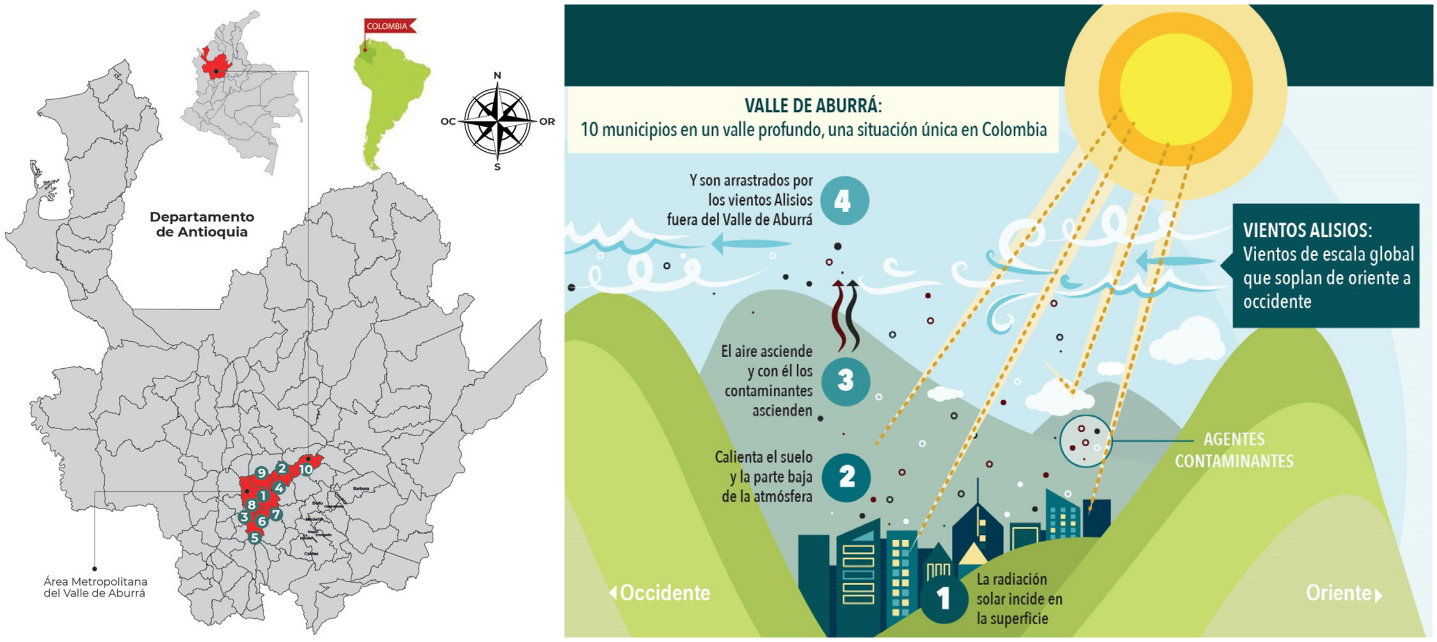

Figure 1. Scenario - Aburrá Valley. Source: Map (Asoareas, 2021), Image (SIATA, 2016).

strategies that contribute to the GHG mitigation challenges in the region so that these can align with public climate change policies. In this case, the city of Medellín – Colombia, has been chosen, taking as a reference the Climate Action Plan PAC 2020 -2050 (Mayor's Office of Medellín, 2020) for the metropolitan nucleus of the Aburrá Valley.

The current phase of the research collates a data survey associated with the properties of aggregates from different quarries across the Aburrá Valley Metropolitan area in the Antioquia department in Colombia. Given the topographic and climatological characteristics, this territory is defined as an atmospheric basin (AMVA, 2015), as mountains delimit its space, leading to the concentration and reaction of gases and air pollutant particles that are not entirely displaced by the winds (Figure 1).

The mountainous perimeter conditions the distribution generated by the trade winds system; therefore, the phenomenon worsens in some seasons. (Agusti-Panareda et al., 2019; B. Liu et al., 2023; SIATA, 2016). A local study (AMVA, 2017) indicates that this type of condition generates a concentration effect characterized by a low-altitude atmospheric limit and high cloud cover, limiting the penetration of solar radiation and causing air cooling. This added to the weak winds, limits the dispersion of particulate matter and other pollutants. This situation is exacerbated by a growing population density of 3557 inhabitants /km^2, which demands the construction of typical buildings, with an average of 30 floors, that use structural systems based on reinforced concrete walls. This results in an accelerated increase in concrete production and, consequently, in the exploitation of its raw materials.

In this scenario, pollution episodes are generated that are greatly accentuated by the load generated by the car fleet. The PAC 2020-2050 indicates that: "the proportion of contribution to pollution by industrial sources is close to 30%, while mobile sources generate about 69% of the atmospheric emissions evaluated and, in particular, are responsible for 91% of the PM 2.5 emissions" (Mayor's Office of Medellín, 2021). The impact of the vehicle fleet constitutes one of the fundamental GHG variables for the region, particularly for concrete production activities, as the intensive use of aggregates (sand/gravel) and their transport from the quarries implies a constant circulation of cargo vehicles needed for their on-site production.

The recognition and reflection on this situation in the environment should favor the development of a sustainable awareness in any economic activity linked to the construction value chain. One of the critical benefits of this lies in the educational processes, where awareness allows students to develop systemic thinking that leads them to evaluate the impact of their decision-making and the ability to manage carbon (CLC, 2016) through the acquisitions of resources throughout their life cycle (Bohvalovs et al., 2023; Martinsone et al., 2023). For the construction economic sector, this can represent progress towards the sustainable development of buildings and the dissemination of relevant information related to sustainability.

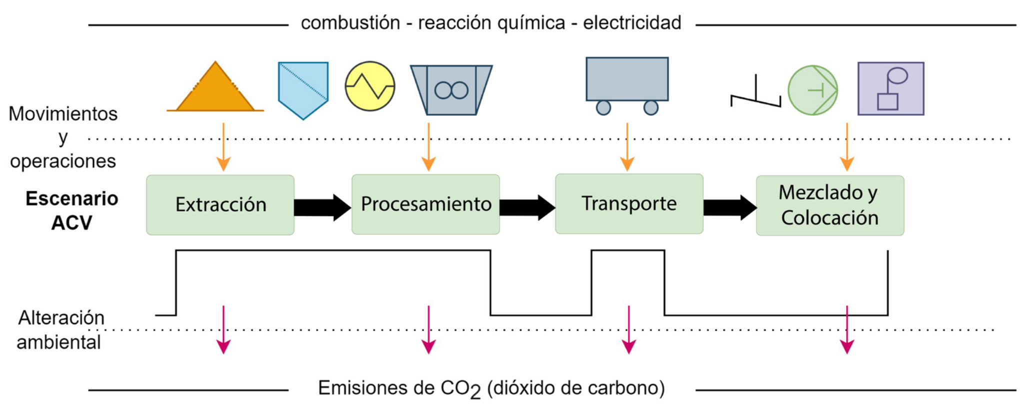

Figure 2. Holistic context of the concrete emission cycle. Source: Preparation by the authors.

CONCRETE AND ENVIRONMENT RELATIONSHIP

Concrete is the most used artificial material in the world, with more than 25 Gt/year (De Andrade Salgado & De Andrade Silva, 2022; Gursel et al., 2014). It comprises four essential ingredients: water, cement, gravel as coarse aggregate (CA), and sand as fine aggregate (FA). These raw materials constitute one of the most extracted mineral resources on the planet (Del Rey Castillo et al., 2020). In addition, this product includes stages in its energy-intensive manufacturing process and operations, which are responsible for much of the greenhouse gas emissions. The global cement industry produces 4.1 billion tons annually, accounting for 8-10% of anthropogenic CO_2 emissions globally (Poudyal & Adhikari, 2021; Vázquez-Calle et al., 2022). In addition, studies indicate that for every kilogram of cement produced, 0.80-0.90 kilograms of carbon dioxide are released into the environment, making cement production the leading GHG producer after electricity production plants (Ajayi & Babafemi, 2024). According to Duque (2020), a typical concrete with a strength of 25 MPa generates 0.29 t CO_2 —eq/m^3 and cement production represents 82% of this figure.

The significant increase in concrete use in recent decades, due to the increase in the world population and the corresponding demand for infrastructure, has caused a significant environmental problem (Youssf et al., 2024). Figure 2 presents a comprehensive view of the raw material's life cycle stages, from extraction to processing and site placement. Due to access restrictions, in this scenario, the research project involves only the characterization of coarse and fine aggregates from different sources to generate an inventory of this particular line. The details of this process are described in the methodology.

These resources are in high demand in Colombia, and the consumption trend is growing. The country's concrete production volumes reached a production of 6.9 million m^3 from June 2022 to June 2023, a growth of 3.7% compared to June 2022. 68.0% of the production was oriented to housing, 23.3% to civil works, and 18.6% to buildings. For the same period, the department of Antioquia region, comprising 123 municipalities, in which Medellín and its Metropolitan Area are located, showed the highest growth, with an increase of 17.6%, a dispatch of 179,855 tons of cement, and a total concrete production of 89,376 m^3 (DANE, 2023).

These statistics underline the importance of LCA in concrete production and monitoring the production and transport of inputs to develop data and prepare GHG projections associated with these volumes and how, from early stages, to interpret the impacts for the definition of mitigation strategies.

In Colombia, the design of concrete mixtures currently does not include tools or practices for quantifying the environmental impact associated with the generation of CO_2 and its impact on climate change because there are disjointed methodologies for this purpose. Based on computer solutions or tools such as Product Life Cycle Management or PLM (Product Life Management), the selection criteria for smarter supply chains can be favored and, therefore, contribute with technological means to the context of Industry 4.0 and, consequently, to the explicit implementation of public policies (Stegmann, 2020). These policies, aimed at the country's sustainable development, should encourage energy efficiency and promote sustainable construction practices. In this way, it aligns with the fulfillment of the Sustainable Development Goals (SDGs), which emphasize the creation of sustainable cities and communities and consumption and production patterns to reduce greenhouse gases (GHG) by 20%.

Table 2. Approaches related to GHG mitigation and environmental impacts. Source: Preparation by the authors.

Approach	Framework	Technical	Source
Concrete Optimization	Optimization techniques	Predictive models AI - ML	(Zandifaez et al., 2023)
		Multi-objective optimization Inventory allocation	(Z. Liu et al., 2023)
	Selection of aggregates	Artificial aggregates	(Siamardi et al., 2023)
		Calcareous	(Jamil et al., 2023)
LCA	Life Cycle Assessment	Petrographic analysis	(Ghadir et al., 2021)
	Environmental Impact Assessment	Contraction/reduction Recycled materials	(Goyal et al., 2023)
		Comparative studies Decarbonization strategies	(Bush et al., 2022)

Table 3. Studies on optimization techniques to mitigate CO2 and GEI. Source: Preparation by the authors.

Source	Study	Optimization techniques	Sustainability Parameters
Naseri et al., 2023 North America-Oceania	A novel evolutionary learning to prepare sustainable concrete mixtures with supplementary cementitious materials	Evolutionary learning algorithms, optimization programming	Reduction of global warming potential, energy consumption, material consumption, embodied CO_2
Wang et al., 2022 Asia	Energy Optimization Design of Limestone Hybrid Concrete in Consideration of Stress Levels and Carbonation Resistance	Genetic algorithm, water cycle algorithm	Mechanical strength, carbonation resistance, environmental impact, embodied energy
Naseri et al., 2020 Asia-North America	Designing sustainable concrete mixture by developing a new machine-learning technique	Machine learning algorithms, statistical modeling	Reduction of embodied CO_2, energy consumption, material consumption
Khan, Do and Kim, 2016 Asia	Cost-effective optimal mix proportioning of high-strength self-compacting concrete using response surface methodology	Response surface methodology (RSM)	Costs, environmental impact, compressive strength, durability
Ibe et al., 2022 Africa	Optimization and Simulation of Saw Dust Ash Concrete Using Extreme Vertex Design Method	Extreme vertex design	Reduction of embodied CO_2, durability, mechanical properties
Ewa et al., 2023 Africa	Optimization of saw dust ash and quarry dust pervious concrete's compressive strength using Scheffe's simplex lattice method	Scheffe's simplex network method	Compressive strength, environmental impact, sustainability of materials
Kim et al., 2022 North America	OpenConcrete: a tool for estimating the environmental impacts of concrete production	Impact scenario analysis to produce a representative concrete mix in the United States	Emissions of GHG, nitrogen oxide, sulfur oxide, and volatile organic compounds, embedded energy, water consumption, and emissions of particles smaller than 2.5 microns (PM2.5).
Berkeley, n.d.	Green Concrete LCA Web Tool	Quantification of the environmental impacts of the production of concrete and its components (such as cement, aggregates, additives, and supplementary cementitious materials).	GHG emissions, embedded energy.

The most recent studies address combined frameworks and explore properties of traditional materials and new additions, looking for efficiencies and optimizations that contribute to lower consumption rates of cementing material (Portland cement) and a lower carbon footprint (Table 2).

From the point of view of environmental protection, these investigations are associated with sustainable design and contribute to the mitigation of impacts. This work is framed in the same line as the optimization and efficient concrete dosing to promote best practices and value criteria that reduce the effects generated by human activity around

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construction as proposed (Oladazimi et al., 2020). Although the efforts are not yet integrated and the environmental challenges of cement and concrete production persist (Belaïd, 2022b), research processes and analytical models based on ISO 14044 continue to contribute to knowledge in order to approximate standardized criteria for advanced decision-making. Table 3 records specific studies aimed at GHG optimization and mitigation. In addition, it has been observed that the computer tools developed allow quantifying the environmental impacts associated with concrete mixtures. However, these tools have limitations because they do not integrate phases such as the mixtures' design depending on the materials' properties specific to the place and the use of established cement contents.

In addition, these studies usually focus only on quantifying greenhouse gases and embedded energy. However, the effect that variables such as the percentage of moisture, aggregate sizes, and other physical properties of materials may have is not clearly evident. Due to their stochastic nature, these variables can influence the results of the developed tools.

Therefore, this study focuses on applying Life Cycle Analysis (LCA) to the design of concrete mixtures in the Metropolitan Area of the Aburrá Valley, Colombia. Its purpose is to demonstrate that the identification, characterization, correct choice, and optimization of the proportions of concrete mixtures can reduce CO_2 emissions, energy consumption, and other environmental impacts. This is especially relevant in a highly informal sector in Colombia, where there are gaps in the objective criteria for defining the sources of raw materials for producing concrete mixtures. In addition, the lack of a selection with environmental criteria from the methodological point of view hinders an agile response to the execution of infrastructure works. This study seeks to raise awareness and guide decision-makers in the execution and design of construction processes by selecting the raw materials used to manufacture concrete mixtures in different buildings. To contribute to the solution, a methodology is proposed that, based on the identification of the sources, the characterization of the materials and their environmental statement, together with the articulation of concrete mixture design techniques, can generate environmental and economic benefits in the production of concrete, in addition to highlighting the need for the construction sector to implement this type of practices and initiatives.

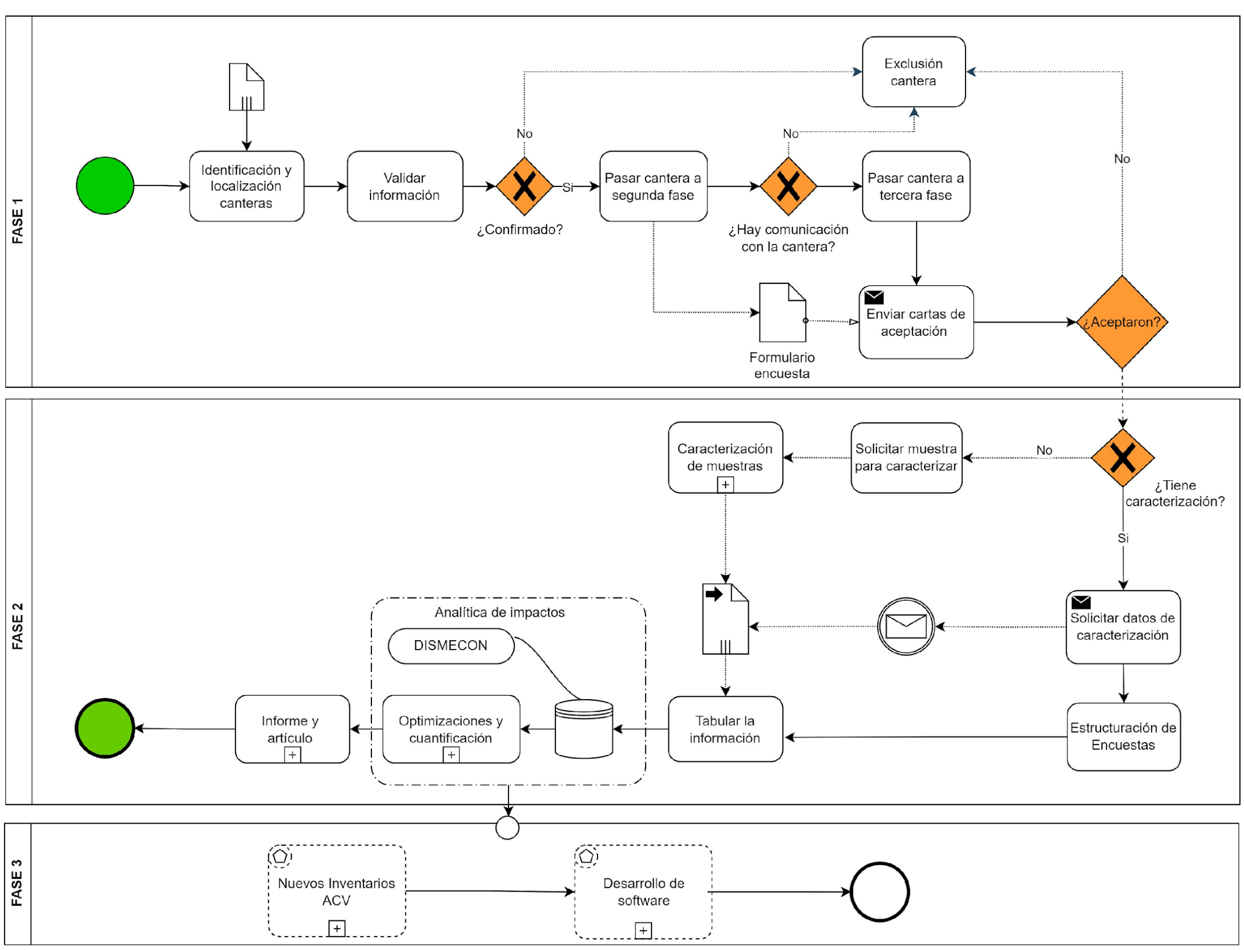

Figure 3. Phases of the methodological process. Source: Preparation by the authors.

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METHODOLOGY

This research considers three phases framed in the LCA. In its first and second phases, the on-site concrete production scenario is contemplated and focuses on aggregate management as the first inventory for evaluating GHG emissions and their relationship with the design of mixtures. The inventories associated with ready-mixed concrete (production in industrialized plants) are not addressed in this article; this is proposed for a future phase 3.

Data of the characterization of the materials produced in quarries (n=13) located in the Metropolitan Area of the Aburrá Valley, Table 2, are used to determine the dosages of optimal concrete mixtures from the economic and environmental point of view. Figure 3 presents the proposed methodological process, highlighting the first two phases, the progress of the current research, and the stage 3 scenario where the development of a GHG estimation software for concrete in situ and premixed will be addressed.

Figures 4 and 5 show the characterization of the quarry materials, fine and coarse aggregates, under normative parameters (Colombian NTC Technical Standards and their equivalents to ASTM standards). Table 4 identifies the distribution of raw material sources in the 10 municipalities of the Metropolitan Area of the Aburrá Valley for a total of 13 quarries between fine and coarse aggregates.

Figure 4. Protocols conducted to determine the different normative tests and data sources comprising the characterization of the coarse aggregates (CA).

The data obtained through the characterization tests allow the parameterization of their properties based on the water-cement-aggregate ratio to ensure the required strength. Concrete quality depends on several factors; however, the design and the choice of raw materials, such as aggregates, are critical elements in its durability (Uthaman & Vishwakarma, 2023).

ENVIRONMENTAL INVENTORY OF MATERIALS

The impact analysis used the theoretical framework that analyzes the processes related to concrete production in the Metropolitan Area of the Aburrá Valley. The database was consulted for the inventory of the environmental statement of the concrete mixtures' materials (*THE INTERNATIONAL EPD SYSTEM*, 2024), seeking the companies supplying Portland cement and fine and coarse aggregates from the geographical place under study. Only two companies were identified: Argos Cement

Table 4. Location of sources of aggregates. Source: Preparation by the authors.

Municipality	Number of Quarries Evaluated
Medellín (Dtto.)	4
Girardota	3
Caldas	3
Itagüí	1
Bello	2

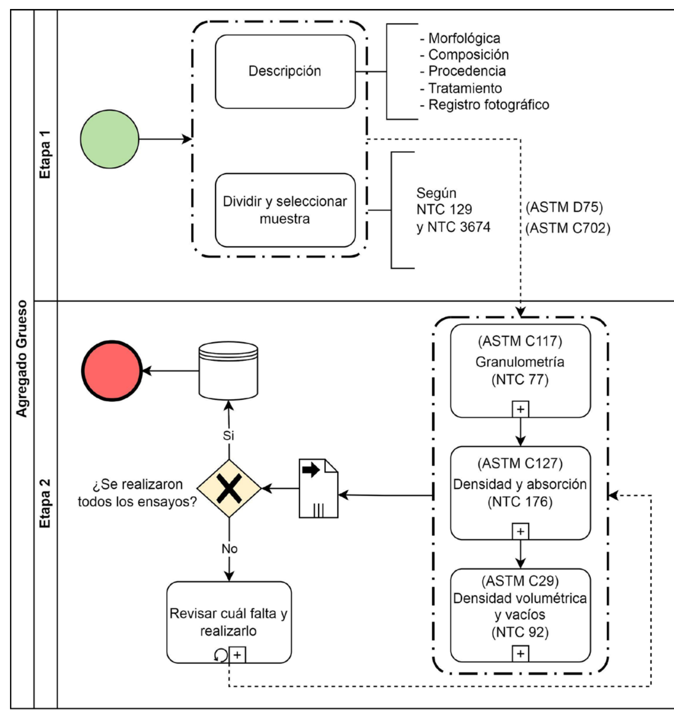

Figure 4. Methodological process of CA characterization. Source: Preparation by the authors.

(Portland Cement Association, 2014) for cement and (Industrial Conconcreto S.A.S., 2019) for fine and coarse aggregates

To make an environmental inventory of the materials, the following environmental hypothesis is proposed: *"Respectively, the fine aggregate and coarse aggregate materials of the Metropolitan Area of the Aburrá Valley, due to their geology and form of extraction, present an identical EPD (Environmental Product Declaration) to those reported by Industrial Conconcreto."*

The declared functional unit is one metric ton for fine and coarse aggregates, specifically sand for concrete and coarse aggregate, with nominal maximum sizes of 19 mm and 25 mm. The indicators are presented in Table 5.

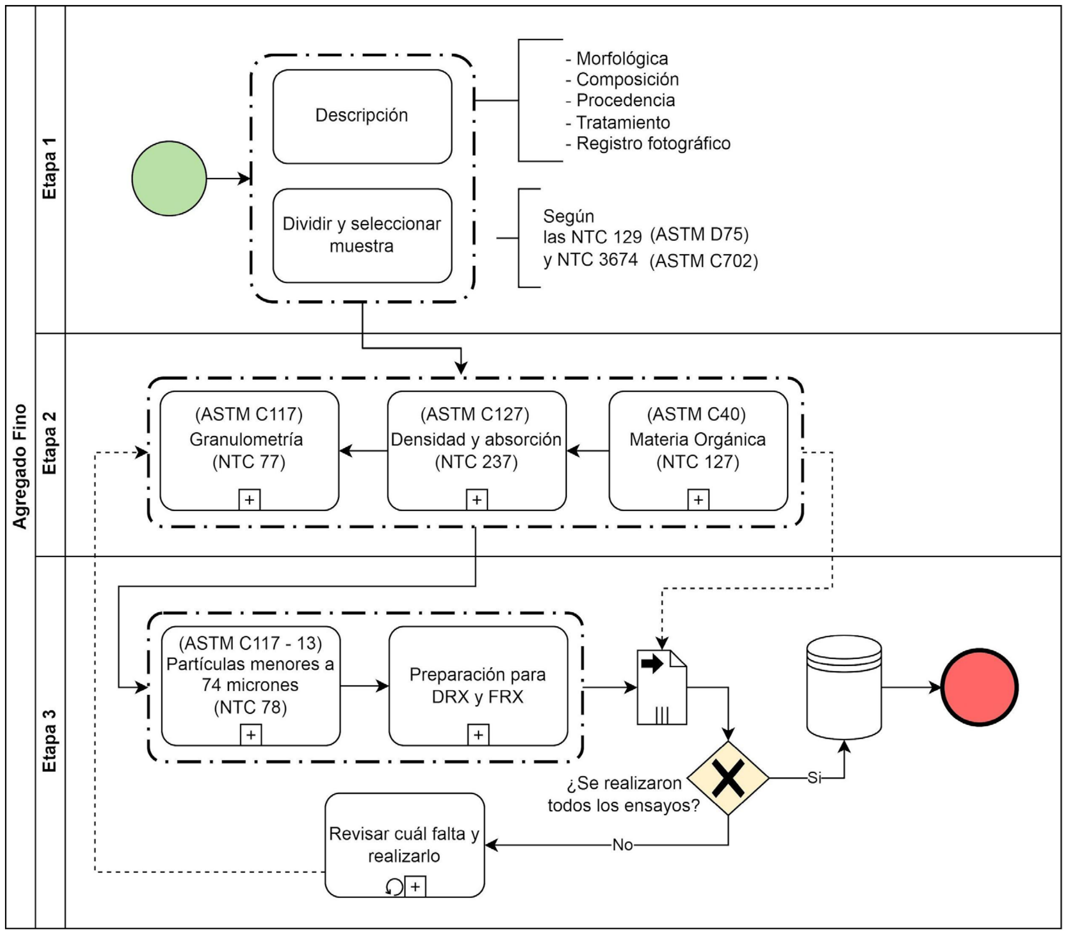

Figure 5. Methodological process of FA characterization. Source: Preparation by the authors.

Table 5. Environmental impact indicators cement and aggregates. Source: Adapted from Industrial Conconcreto S.A.S. (2019) and Portland Cement Association (2014).

Indicator	Indicator Abbreviation	Unit	Fine Aggregate	Coarse aggregate	Cement
Global Warming Potential (100 years)	IA1	kg CO_2-eq	3.34	2.70	892.00
Marine eutrophication potential	IA2	kg N-eq	0.013	0.010	1.100
Freshwater phosphate ions' eutrophication potential	IA3	kg PO_4^{3-}- eq.	0.006	0.004	0.000
Freshwater eutrophication potential	IA4	kg P-eq.	0.00032	0.00025	0.00000
Eutrophication potential, accumulated excess	IA5	mol N-eq.	0.130	0.107	0.000
Non-renewable Primary Energy: Fossil	IA6	MJ	56.75	42.76	4660.00
Renewable Primary Energy: Solar, Wind, Hydro-electric, Geothermal	IA7	MJ	6.91	6.27	95.50
Total embedded energy	IA8	MJ	63.66	49.02	5243.40
Non-renewable Material Resources	IA9	kg	0	0	1240
Renewable Material Resources	IA10	kg	0	0	3.42
Net Freshwater	IA11	m^3	301.70	145.50	9240.00
Non-hazardous Waste Generated	IA12	kg	111.30	51.50	10.50
Hazardous Waste Generated	IA13	kg	0.0012	0.0011	0.0511

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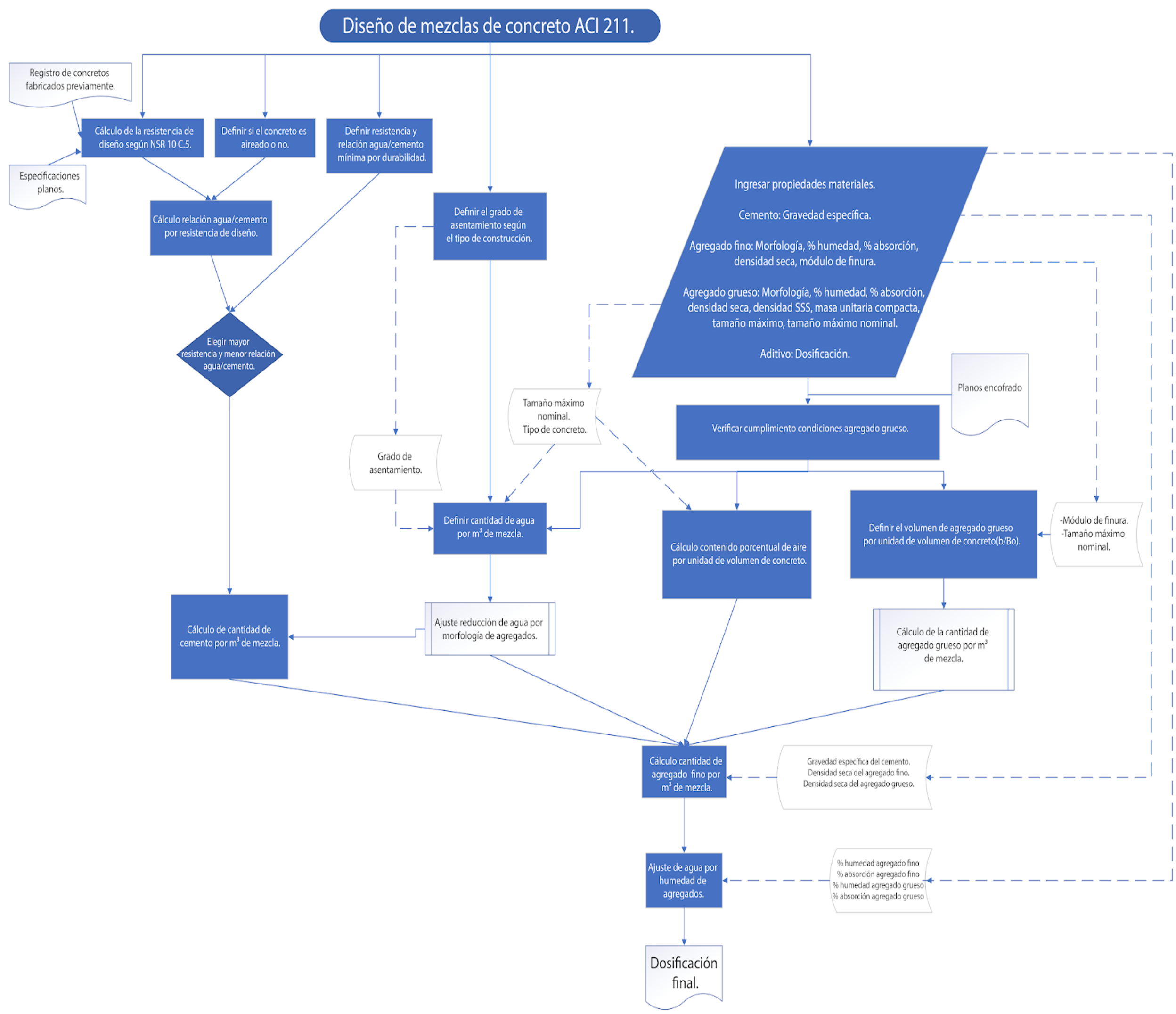

Figure 6. Operation framework - DISMECON software. Source: Preparation by the authors.

ENVIRONMENTAL QUANTIFICATION AND OPTIMIZATION OF CONCRETE MIXTURES.

The materials' environmental characterization data were tabulated and placed in the DISMECON base software (Restrepo et al., 2020). This tool can be used to estimate or approximate the initial quantities of materials for the design of mixtures. The software is based on the A.C.I 211 methodology (American Concrete Institute). It calculates the dosage of the materials according to the performance conditions (compressive strength, durability, workability) required of the concrete, from the physical properties of the aggregates such as density, unit weight, nominal maximum size, fineness modulus, density and absorption, among others (Table 5 and Table 6), and data of the mixtures such as the desired consistency, the application of the concrete, laying and formwork conditions, the exposure conditions, the w/c ratio, or the resistance. The software's operation can be seen in Figure 6.

The computer tool is modified in its programming to include the structured data and process the indicators of the environmental inventories obtained in Table 5. With this structure, the framework proposed by NTC-ISO 14044 is configured as follows: a) Objective and scope, b) Analysis of the life cycle inventory, c) evaluation of the life cycle impact, and d) interpretation.

Regarding the optimization scenarios, an optimization plan is designed based on the aggregates (FA/CA). To do this, 8 fine aggregates (Table 6) and 4 coarse aggregates (Table 7) were evaluated. To establish a baseline in the simulation of concrete mix designs, a structural concrete of the lowest possible resistance is considered according to the 2010 earthquake-resistant standard (NSR) and the lowest settlement contemplated in the concrete mix design methodology. These parameters generate the scenario of less cement demand for this type of concrete and, consequently, the lowest environmental loads. The design parameters have the following configuration:

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Table 6. Ratios of FA types - Optimization for application. Source: Preparation by the authors.

Fine Aggregate (FA)	Fineness Modulus [ASTM C117]	Dry Bulk Density (kg/m3) [ASTM C127]	Absorption (%) [ASTM C127]	Morphology
1F	3.00	2709	1.90	Crushed
2F	3.76	2620	0.87	Crushed
3F	2.70	2901	1.03	Crushed
4F	3.01	2602	2.40	Crushed
5F	3.00	2646	1.98	Crushed
6F	3.14	2550	1.21	Crushed
7F	4.00	2750	1.07	Crushed
8F	3.40	2786	0.99	Crushed

Table 7. Ratios of CA types - optimization for application. Source: Preparation by the authors.

Coarse Aggregate (CA)	Max size (mm) [ASTM C117]	Nominal maximum size (mm) [ASTM C117]	Dry bulk density (kg/m3) [ASTM C127]	Compact unit mass (kg/m3) [ASTM C29]	Absorption (%) [ASTM C127]	Morphology
1C	50.0	37.5	2863	1499	0.24	Crushed
2C	37.5	25.0	2735	1635	1.50	Crushed
3C	25.0	19.0	2770	1610	0.86	Crushed
4C	25.0	19.0	2862	1707	0.92	Crushed

TYPE OF CONVENTIONAL CONCRETE

- Non-aerated concrete.
- Design resistance 21 MPa.
- Type of construction: Mass concrete.
- Settling: 50 mm.

The analysis of the additives that modify the properties in the plastic state is not included because the case study represents a concrete mixture with easily achievable mechanical characteristics. Additionally, the impacts reported by the European Federation of Concrete Admixtures Associations Ltd (EFCA, 2015) only include the energy demands and not the environmental loads associated with the chemical processes of the additives, thus limiting the scope.

RESULTS AND DISCUSSION

CHARACTERIZATION OF AGGREGATES

The results of the characterization of the aggregates from the quarries evaluated in the Metropolitan Area of the Aburrá Valley show variations in physical properties with some atypical data that may be associated with changes in production processes.

For the fine aggregates, it is observed in Figure 7 that the average value of the absorption percentage is 1.63%, which is in line with the ACI 211 methodology, which establishes 2% as the maximum absorption of the aggregates. On the other hand, about 29% of the data has absorption values greater than 2%. Additionally, the humidity percentages vary between 0% -8%. This range of values is accepted to prepare concrete. The fineness moduli obtained between 2.8 and 3.2 are ideal values for the sand used to manufacture concrete. However, 50% of the aggregates have a Fineness Modulus (FM) between 3.6 and 4.3, values associated with arenon, characteristic of very coarse sands that can induce very rough and unmanageable concrete mixtures. Finally, the Dry Bulk Density (DBD) has values around 2100 kg/m^3 and 2900 kg/m^3.

Similarly, it is observed from Figure 8 that

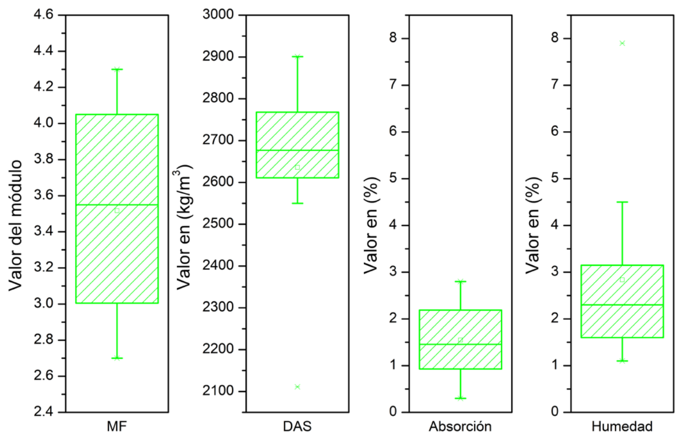

Figure 7. Characterization properties of Fine Aggregates. Source: Preparation by the authors.

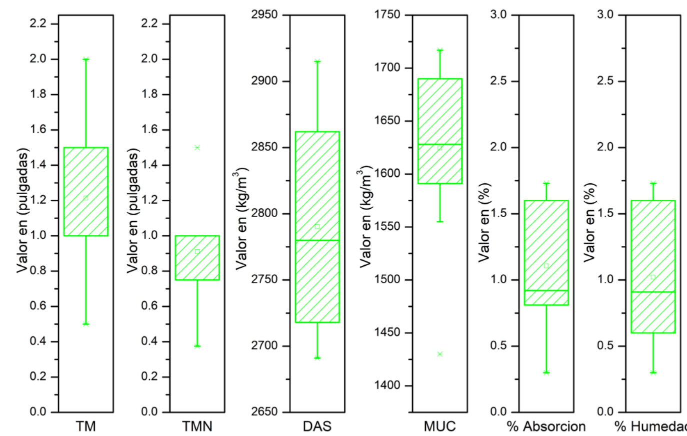

Figure 8. Characterization properties of Coarse Aggregates. Source: Preparation by the authors.

approximately 100% of the coarse aggregates have absorption percentages lower than 2%, qualifying them as suitable for use. The Maximum Size (MS) and Nominal Maximum Size (NMS) account for the tendency (75%) to produce thick aggregates with sizes between 1½" (38 mm) and 2" (50.8 mm) due to the need to meet, in steel-reinforced concrete construction systems, the geometric requirements of the formwork and the distances between the rebars. The Compact Unit Mass (CUM) was located between 1425 kg/m^3 and 1720 kg/m^3, and the humidity percentage was between 0% and 1.8%, the latter in the range of accepted values for concrete preparation. When comparing Figure 7 and Figure 8, a higher average Dry Bulk Density (DBD) is observed for coarse aggregates (2790 kg/m^3) than fine aggregates (2628 kg/m^3), which is associated with the number of voids between the fine aggregate particles, requiring in these cases a greater amount of mortar paste to achieve adequate workability of the mixture (Pérez et al., 2022).

DESIGN OF MIXTURES

Under the specified conditions and raw materials, the concrete design resulted in 32 possible dosages detailed in Table 8. 3 trends in cement consumption were identified (266 kg, 290 kg, 316 kg), which are related to the maximum size of coarse aggregate. This implies a reduction of up to 15.8% in the demand for cement when comparing the maximum and minimum values and an increase in aggregate consumption of up to 7.2%. In addition, an increase in water consumption of up to 15.7% is observed when comparing the average water consumption between the mixtures with the highest and lowest demand for cement. When considering the cost and the high environmental impact of cement, these findings suggest the importance of more informed decision-making by project developers to optimize both the cost and the environmental impact of the concrete mixtures to be produced.

Table 8. Dosages of concrete mixtures. Source: Preparation by the authors.

Mix ID	Mix	Concrete Dosage				Quantities x 1 m3 of Concrete						
		Cement (parts)	Fine Aggregate (parts)	Coarse Aggregate (parts)	Water/ cement ratio	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Total aggregates (kg)	Average Aggregate Total (kg)	Water (L)	Average Water (L)
1	3F1C	1	4.408	4.057	0.555	266	1172.6	1079.3	147.7	2165.1	157.1	152.8
2	8F1C	1	4.618	3.663	0.555	266	1228.3	974.4	147.5		145.7	
3	7F1C	1	4.883	3.325	0.56	266	1298.8	884.4	149		147.7	
4	1F1C	1	4.277	3.888	0.591	266	1137.6	1034.3	157.1		161.7	
5	5F1C	1	3.646	4.463	0.62	266	969.8	1187.2	164.9		164.9	
6	4F1C	1	4.113	3.883	0.608	266	1094	1032.8	161.7		148.6	
7	2F1C	1	4.528	3.46	0.548	266	1204.5	920.4	145.7		149	
8	6F1C	1	4.096	3.809	0.559	266	1089.5	1013.3	148.6		147.5	

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Mix ID	Mix	Concrete Dosage				Quantities x 1 m3 of Concrete						
		Cement (parts)	Fine Aggregate (parts)	Coarse Aggregate (parts)	Water/ cement ratio	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Total aggregates (kg)	Average Aggregate Total (kg)	Water (L)	Average Water (L)
9	3F2C	1	3.451	3.834	0.593	290	1000.7	1111.8	172	2040.0	179.6	174.6
10	8F2C	1	3.716	3.439	0.588	290	1077.6	997.4	170.6		168.4	
11	7F2C	1	4.008	3.101	0.589	290	1162.3	899.3	170.9		172	
12	1F2C	1	3.39	3.665	0.619	290	983	1062.8	179.6		183.6	
13	5F2C	1	3.311	3.665	0.621	290	960.2	1062.8	180		180	
14	4F2C	1	3.261	3.659	0.633	290	945.8	1061.1	183.6		172.1	
15	2F2C	1	3.689	3.24	0.581	290	1069.8	939.5	168.4		170.9	
16	6F2C	1	3.264	3.586	0.593	290	946.7	1039.9	172.1		170.6	
17	3F4C	1	3.253	3.403	0.565	316	1027.9	1075.4	178.5	2008.9	185.9	181.3
18	3F3C	1	3.341	3.21	0.562	316	1055.7	1014.3	177.6		175	
19	8F4C	1	3.492	3.025	0.562	316	1103.4	955.9	177.7		177.6	
20	1F4C	1	3.191	3.241	0.59	316	1008.3	1024.2	186.6		190.1	
21	7F4C	1	3.758	2.701	0.565	316	1187.6	853.5	178.6		186.2	
22	8F3C	1	3.567	2.872	0.56	316	1127.2	907.6	176.9		178.1	
23	5F4C	1	3.117	3.241	0.592	316	984.9	1024.2	186.9		177.9	
24	7F3C	1	3.824	2.547	0.563	316	1208.5	805	177.9		176.9	
25	1F3C	1	3.269	3.057	0.588	316	1033	966	185.9		186.6	
26	4F4C	1	3.07	3.236	0.603	316	970	1022.5	190.7		175.8	
27	2F4C	1	3.462	2.831	0.556	316	1093.9	894.5	175.8		178.5	
28	5F3C	1	3.193	3.057	0.589	316	1009	966	186.2		190.7	
29	6F4C	1	3.071	3.166	0.566	316	970.4	1000.3	178.9		186.9	
30	4F3C	1	3.145	3.052	0.602	316	993.7	964.4	190.1		178.9	
31	2F3C	1	3.528	2.67	0.554	316	1114.8	843.6	175		178.6	
32	6F3C	1	3.143	2.986	0.564	316	993.1	943.5	178.1		177.7	

Figure 9 illustrates the behavior of the material consumption of the different dosages for a concrete of 21 MPa from Table 8. There is evidence of a reduction in the average water demand of up to 15.7% due to a decrease in cement consumption from these. Additionally, mixtures with the same cement consumption can be optimized by reducing the average aggregate consumption by up to 6.6%. Thus, it is evident that the correct choice and combination of materials to make concrete mixtures can generate economies and their respective benefits without requiring major efforts.

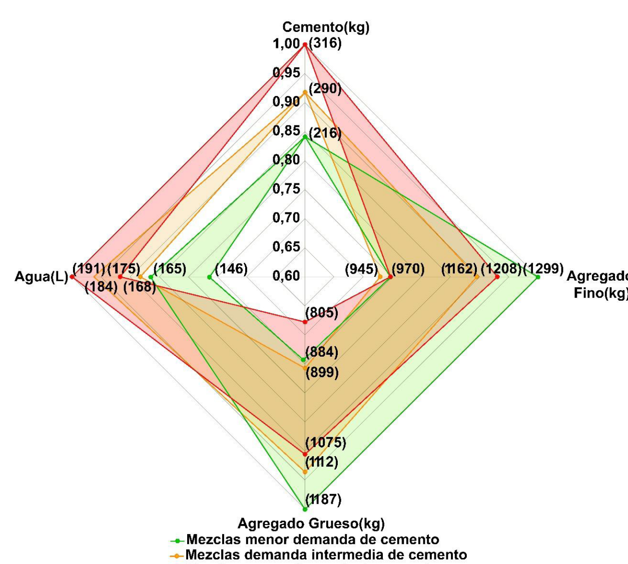

Figure 9. Relationship of consumption of materials of different mixtures for the same resistance target 21 MPa. Source: Preparation by the authors.

ECONOMIC QUANTIFICATION

The cost per cubic meter of each concrete mixing ratio of 21 MPa was calculated using the unit values expressed in USD/kg of the raw materials used in each mixture. As of March 2024, the commercial values of primary inputs in Colombia

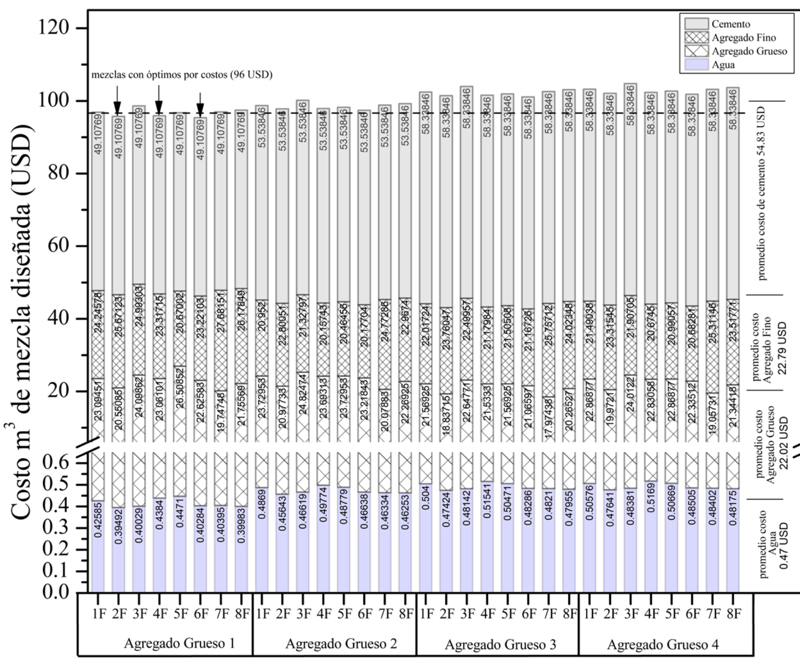

Figure 10. Cost of concrete mixtures. Source: Preparation by the authors.

were converted by an equivalence factor of 3900 Colombian pesos per American dollar. When analyzing the economic efficiency of the different proposed concrete mixtures, as seen in Figure 10, the raw material cost for 1 m^3 of concrete varies between 95.36 USD and 104.74 USD, representing an economic optimization of up to 9%. It is evident that this reduction is directly associated with the decrease in the demand for cement, which is the most expensive component. In addition, it is observed that the 6F1C mixture, which has the lowest cost, achieves a balance in aggregate costs and has the lowest consumption among mixtures that share the same cement consumption index.

ENVIRONMENTAL QUANTIFICATION

The mixture with the lowest production cost (6F1C) primarily exhibits lower environmental impacts regarding CO_2- eq emissions, O_3-eq, embedded energy, and freshwater consumption. This is evidenced in Figure 11, built by evaluating the environmental impacts of the 32 designed mixtures and using the environmental inventory of the materials (cement and aggregates). In contrast, given the increase in the demand for aggregates in this mixture and the production process, the analysis shows higher levels of water pollution in lakes, ponds, rivers, and reservoirs, registering more significant impacts in terms of eutrophication and generation of non-hazardous waste.

Figure 12 quantifies the environmental impacts

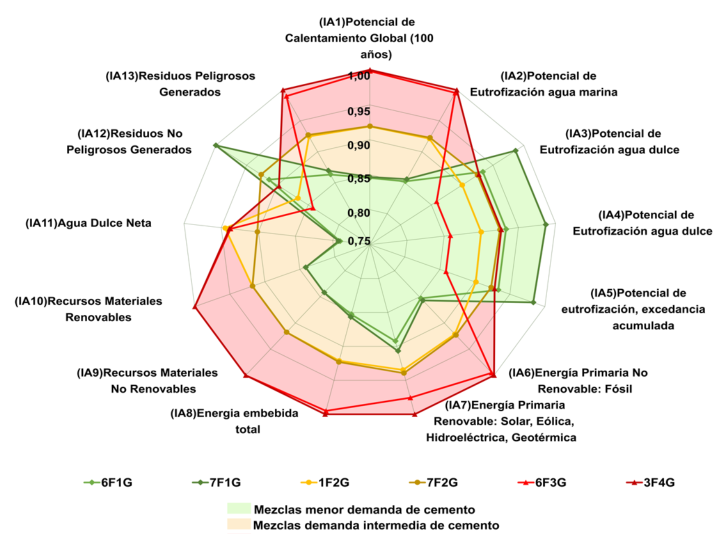

Figure 11. Relationship environmental impacts concrete mixtures. Source: Preparation by the authors.

associated with the production of 1 m^3 of concrete according to the specifications of the proposed conventional concrete type (21 MPa). CO_2-eq emissions are highlighted, which range between 243.7 kg and 288.2 kg; total embedded energy, varying from 1513.8 MJ to 1775.1 MJ; and freshwater consumption, between 156.8 L and 200 L. These values suggest the possibility of achieving 15.4% reductions in CO_2 emissions, 14.7% in embedded energy, and 21.5 % in freshwater consumption.

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	IA 1		IA 2	IA 3	IA 4	IA 5	IA 6	IA 7	IA 8		IA 9	IA 10	IA 11	IA 12	IA 13
Mezcla	kg CO2-eq	Promedio kg CO2-eq	kg N-eq	kg PO43- eq.	kg P eq.	mol N eq.	MJ	MJ	MJ	Promedio MJ	kg	kg	L	kg	kg
1F1G	243,9		0,320	0,0109	0,0006	0,3	1348,3	39,7	1517,9		329,8	0,9	166,8	182,7	0,016
2F1G	243,8		0,320	0,0108	0,0006	0,3	1347,3	39,5	1516,5		329,8	0,9	155,4	184,2	0,016
3F1G	244,1		0,321	0,0113	0,0006	0,3	1352,3	40,3	1522,3		329,8	0,9	157,4	188,9	0,016
4F1G	243,7	243,9	0,319	0,0107	0,0006	0,3	1345,8	39,4	1515,0	1517,7	329,8	0,9	171,4	177,7	0,016
5F1G	243,7		0,319	0,0107	0,0006	0,3	1345,4	39,5	1514,7		329,8	0,9	174,6	171,9	0,016
6F1G	243,7		0,319	0,0106	0,0006	0,3	1344,7	39,3	1513,8		329,8	0,9	158,3	176,2	0,016
7F1G	244,0		0,321	0,0112	0,0006	0,3	1351,1	39,9	1520,8		329,8	0,9	158,7	192,9	0,016
8F1G	244,0		0,321	0,0112	0,0006	0,3	1350,9	40,0	1520,7		329,8	0,9	157,2	189,7	0,016
1F2G	264,8		0,345	0,0102	0,0006	0,2	1452,6	41,1	1635,3		359,6	1,0	189,3	167,2	0,017
2F2G	264,8		0,345	0,0101	0,0006	0,2	1452,3	41,0	1634,7		359,6	1,0	178,1	170,5	0,017
3F2G	265,0		0,346	0,0105	0,0006	0,2	1455,7	41,6	1638,8		359,6	1,0	181,7	171,7	0,017
4F2G	264,7	264,8	0,345	0,0100	0,0006	0,2	1450,4	40,9	1632,8	1635,5	359,6	1,0	193,3	163,0	0,017
5F2G	264,8		0,345	0,0101	0,0006	0,2	1451,3	41,0	1633,8		359,6	1,0	189,6	164,6	0,017
6F2G	264,7		0,344	0,0099	0,0006	0,2	1449,6	40,8	1631,8		359,6	1,0	181,7	162,0	0,017
7F2G	265,0		0,346	0,0105	0,0006	0,2	1455,8	41,4	1638,7		359,6	1,0	180,6	178,7	0,017
8F2G	265,0		0,346	0,0104	0,0006	0,2	1455,2	41,4	1638,1		359,6	1,0	180,3	174,3	0,017
1F3G	287,9		0,374	0,0100	0,0006	0,2	1572,5	43,4	1770,0		391,8	1,1	195,6	168,0	0,019
2F3G	287,9		0,373	0,0100	0,0006	0,2	1571,9	43,2	1769,2		391,8	1,1	184,6	170,8	0,018
3F3G	288,1		0,374	0,0104	0,0006	0,2	1575,8	43,8	1773,8		391,8	1,1	187,3	173,0	0,019
4F3G	287,8		0,373	0,0098	0,0006	0,2	1570,2	43,1	1767,5		391,8	1,1	199,8	163,6	0,018
5F3G	287,9		0,373	0,0099	0,0006	0,2	1571,1	43,2	1768,5		391,8	1,1	195,9	165,4	0,018
6F3G	287,7		0,373	0,0097	0,0006	0,2	1569,3	43,0	1766,4		391,8	1,1	187,8	162,4	0,018
7F3G	288,1		0,374	0,0103	0,0006	0,2	1575,6	43,6	1773,3		391,8	1,1	187,5	179,3	0,019
8F3G	288,1	288,0	0,374	0,0103	0,0006	0,2	1575,3	43,7	1773,2	1770,8	391,8	1,1	186,6	175,5	0,019
1F4G	288,0		0,374	0,0102	0,0006	0,2	1573,6	43,6	1771,3		391,8	1,1	196,3	168,3	0,019
2F4G	287,9		0,374	0,0101	0,0006	0,2	1572,9	43,3	1770,4		391,8	1,1	185,4	171,1	0,019
3F4G	288,2		0,375	0,0105	0,0006	0,2	1576,9	44,0	1775,1		391,8	1,1	188,2	173,1	0,019
4F4G	287,9		0,373	0,0099	0,0006	0,2	1571,3	43,3	1768,8		391,8	1,1	200,4	163,9	0,018
5F4G	287,9		0,374	0,0100	0,0006	0,2	1572,2	43,4	1769,8		391,8	1,1	196,6	165,7	0,019
6F4G	287,8		0,373	0,0098	0,0006	0,2	1570,4	43,2	1767,7		391,8	1,1	188,6	162,8	0,018
7F4G	288,1		0,374	0,0104	0,0006	0,2	1576,4	43,7	1774,4		391,8	1,1	188,2	179,4	0,019
8F4G	288,1		0,374	0,0104	0,0006	0,2	1576,0	43,8	1774,0		391,8	1,1	187,4	175,4	0,019

Escala impactos: Mayor

Figure 12. Quantification of environmental impacts in concrete mixtures. Source: Preparation by the authors.

Figure 13 also shows the relationship between the decrease in the production cost of concrete mixing and the decrease in CO_2 emissions, embedded energy, and freshwater. Additionally, the eco-indicator values were determined based on the production cost regarding the categories of Global Warming Potential impact and Total Embedded Energy, as evidenced in Figure 14, where the best performance in the mixtures are precisely the most economical and those that require less Portland cement to achieve the same mechanical resistance. This shows, not only by environmental factors but also by economic factors, the benefit of this type of initiative when choosing aggregates to manufacture concrete on the worksite. Although this work establishes a methodology that shows a quantification of environmental impacts to apply to concrete mixtures designed for 21 MPa, it is possible to use it in different strengths and specifications, establishing environmental impact indicators that are more consistent with the local reality and whose potential use can be scaled to other latitudes that have an environmental product declaration (EPD) for materials and use the A.C.I methodology to design concrete mixtures.

Taking into account that only in 2023 about 89376 m^3 of ready-mixed concrete were produced in the Metropolitan Area of the Aburrá Valley (DANE, 2023), if this amount of concrete is optimized using the methodology used, comparing the most unfavorable case with the most favorable, an estimated saving of about US $838,346.88 could be achieved. In addition, emissions of approximately 3977 tons of CO_2 could be avoided, 23354 GJ of energy saved, and 4022 tons of freshwater

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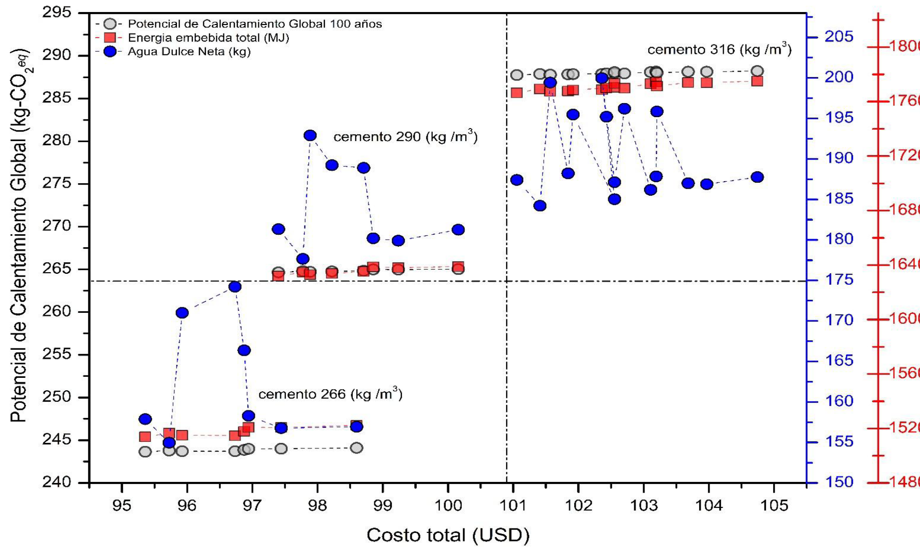

Figure 13. Cost-environmental impact ratio in concrete mixtures of 21 MPa. Source: Preparation by the authors.

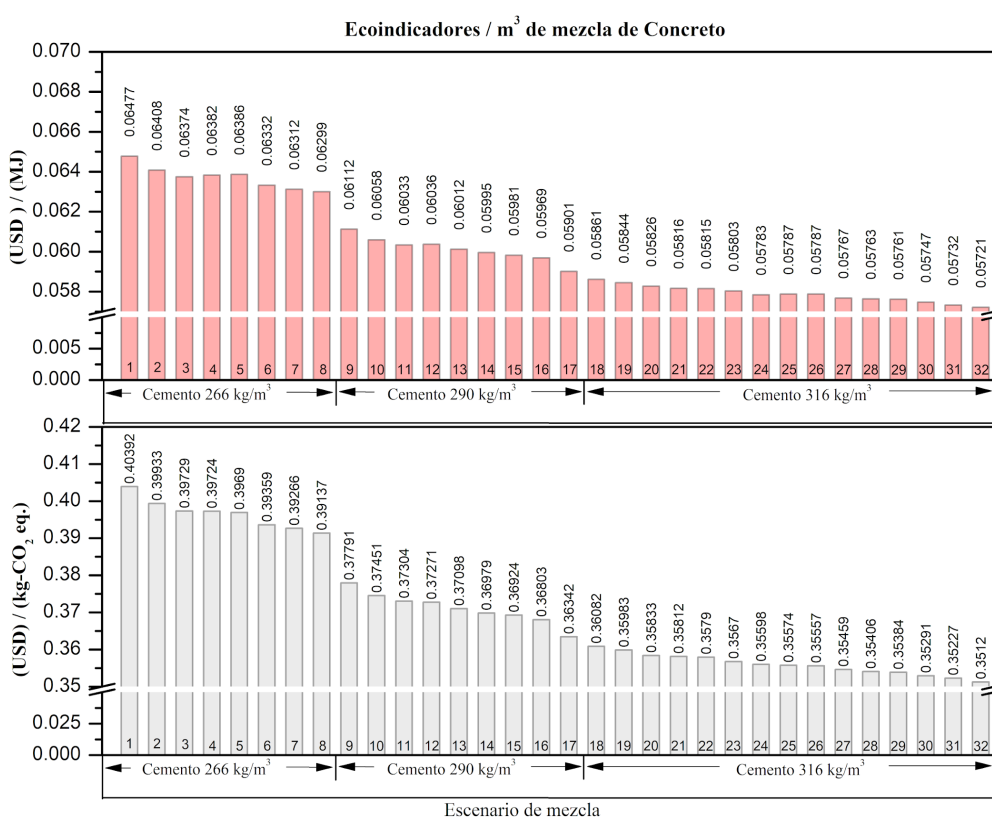

Figure 14. Graph eco-efficiency concrete mixtures of 21 MPa. Source: Preparation by the authors.

conserved. This approach would not only benefit the construction sector but also provide an alternative route to mitigate the environmental impacts associated with this industry.

DISCUSSION

The research shows the possibility of economically and environmentally quantifying and optimizing some production processes in the construction industry. To achieve this, the integration of all the actors involved is required. This includes raw material producers, their level of formalization, and the adoption of best practices, such as environmental declarations of their products (EPD)- similarly, the transport companies and the characteristics of their fleet. Likewise, the architectural and structural designers, with the technical implications of the geometric requirements of the formwork and the distances between the reinforcing bars, stipulate the maximum size of the coarse aggregate to be used in the concrete mixture. This parameter is relevant because it determines the amount of cement required and its corresponding environmental impact. In addition, sustainability aspects should be presented in the construction committees, which allows site managers to play a crucial role in the correct planning and selection of raw material suppliers, taking into account studies such as those proposed in this work, while the builders have the responsibility to materialize what is planned and scheduled.

In this way, under the context of the A.C.I methodology in the design of concrete mixture, the LCA could be integrated to develop a tool that allows optimizing the selection of materials. However, regulations and methodologies for the design of concrete mixtures from other continents can be coupled to implement initiatives of this type. The optimization process allowed identifying the best economic and environmental conditions for designing a mixture for a 21 MPa concrete, defining the selection of fine and coarse quarry aggregates. Although the best route is found, this limits the future implementation to one or two quarry sources, which forces other quarries to improve the production process by implementing innovative technologies that lead to defining the EDP and reducing environmental impacts from the source. Additionally, according to the A.C.I., mixtures with higher MS of the coarse aggregate require a lower cement dosage for a specific strength of concrete. This is a factor to consider in concrete production systems, as the technical literature shows that cement is the indicator that raises costs the most and generates environmental impacts. Thus, builders are called to analyze each technical, economic, and environmental component considering the project being executed.

Both embedded energy and global warming show similar responses in each of the three families of mixtures due to the demand for cement. In many cases, an inverse relationship is observed between water and the indicators of global warming and embedded energy. This pattern is associated with a high dependence on the intrinsic characteristics of aggregates, such as their morphology and degree of absorption. In addition, the results demonstrate the greater eutrophication and generation of hazardous waste from aggregates for the most optimal mixtures. This may be associated with the preparation of the aggregates, as mainly the washing of the material removes particles of size less than 75 μm like silt and clay. This process is required in aggregates as a quality control parameter, and in most cases, this particulate material is taken to tributaries in the form of sludge. This can be a focus of research to recover sludge and develop utilization processes.

Although the proposed environmental hypothesis allowed the development of an optimization tool, the fields associated with the EDPs of all materials must be validated, which evidences a broad effort on the part of private companies and the public sector with the civil, social, and natural responsibility implied by mining exploitation for construction materials.

According to Table 9, the results obtained in this research are consistent with those achieved with other tools for quantifying the environmental impact of concrete mixtures. By comparing the embedded energy results obtained in this study with the simulation results in the tool *"Green Concrete LCA web tool"* (Berkeley, n.d.), a difference of less than 0.85% was evident for all the evaluated mixtures. These results are very similar because the EDPs of cement reported by producers in Colombia are equivalent to the EDPs from the PCA (Portland Cement Association, 2014). However, in the comparison of CO_2 emissions, an approximate difference of 13% is evident. Although this difference between the results of both tools can be classified as small, it is the result of a site-specific environmental load that may depend on the aggregate extraction and production processes in the study region.

To determine system models with more holistic views, it is necessary to incorporate three aspects: i) Use of equipment and technology associated with

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Type of mix (kg Portland cement / m3 of concrete mix)	Calculation tool			
	Developed by Authors - Phase 2 (Figure 3)		Green Concrete LCA web Tool *	
	GWP: Average (kg CO_2 - eq.)	NRE: Average (MJ)	GWP: Average (kg CO_2 - eq.)	NRE: Average (MJ)
266	243.90	1517.70	280.74	1512.53
290	264.80	1635.50	304.79	1629.23
316	288.00	1770.80	330.97	1755.45

* Simulation May 26, 2024, without transportation and making use of Type I Portland cement.

Table 9. Comparative quantification of environmental impact - Other tools. Source: Preparation by the authors.

the design of concrete mixtures on site, as energy consumption and technological obsolescence can be detrimental to the optimization of mixtures. ii) Use of additives to modify rheological properties of mixtures and reduce cement consumption, as well as use of active additives that improve cement performance. iii) Transportation associated with the materials from the source to the construction site could significantly modify the values obtained from the cost and impacts per evaluated mixture. This is due to the trend of an old car fleet with the prevalence of diesel, which is less efficient, generating higher CO_2 emissions. In addition, variables such as the loads transported and the relationship between density and effort per kilometer transported should be analyzed. Finally, it is necessary to implement the proposed analysis in concrete mixtures with higher strength and durability requirements. In this way, it is possible to evaluate the great potential and quantify the possible economic and environmental benefits that can be obtained by carrying out this type of analysis by programming computer tools that allow the creation of inventories and the interaction of large data flow.

CONCLUSIONS

Implementing and integrating tools that use parameterized data allows for identifying an excellent potential for innovation in the different concrete mixture dosing programs, such as the DISMECON software. The synergy between this knowledge allows establishing a new program to quantify the CO_2 emissions and other environmental impact categories.

Based on the design of mixtures and the consideration of the location data of the sources of the aggregates, together with the optimization correlations according to their characteristics, they allow projecting not only the potential impacts in each of the categories of the EDPs used, but also to make estimates as to the cost of producing the concrete. These estimates are based on the different combinations of these materials, making the process very attractive for economic efficiency in producing concrete mixtures. In addition, it promotes the appropriate decision-making about cement resistance and consumption needs.

The modeling allowed identifying optimization processes in using aggregates to manufacture concrete mixtures and to establish the effects of environmental loads when using aggregates of different sizes. Greater impacts of CO_2 emissions and embedded energy demand are found associated with the incremental consumption of cement in the mixtures, this in turn, is more demanded in the designs of mixtures that use coarse aggregate of smaller maximum size, which implies higher costs and CO_2 emissions, up to 15% higher than if they use coarse aggregates of an immediately larger maximum size.

The concrete mixtures with the lowest environmental impact are, in turn, the most economical, given that an analysis of properties (characterizations) of the aggregates is carried out and, based on these, a better proportionality of cement, which shows that sustainability and economic efficiency are compatible and have a high added value for the construction sector.

This research is expected to contribute to promoting strategies to mitigate greenhouse gases (GHG) in the construction sector. In addition, it demonstrates the need to adopt collaborative work methodologies among all actors in the construction sector, highlighting their potential and the benefits this can generate.

The research shows that it is possible to reduce environmental impacts from the fact that Life Cycle Analyses (LCA) are based on evaluations at the level of the appropriate use and optimization of materials, such as concrete, so that they are scalable and comparable, instead of relying exclusively on the implementation of innovative technologies and materials in the future; effectively contributing to the reduction of emissions and the progress towards a more sustainable built environment, more in line with the conclusions of Olsson et al.(2024) on the need to strengthen processes, to subsequently include innovative low-emission materials.

FUTURE WORKS

In future works, transport should be included to consider the site-specific environmental loads, as, in this work, different transport options were not explored nor was it determined how much their impact represents in the life cycle compared to the total impact. In addition, it will be essential to incorporate construction and demolition waste into the processes, adopting a circular engineering perspective to maximize material reuse and minimize waste. Specific eco-indicators should be developed for the construction sector that are complementary and facilitate standardization processes, allowing their comparison and implementation in other latitudes. The tool will have to be taken to the production level, integrating these future works to offer a more complete and sustainable solution in the construction industry.

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