




# Defining sustainability criteria for concrete production in Panama: A participatory approach with industry consultation

## Definición de criterios de sostenibilidad para la producción de hormigón en Panamá: un enfoque participativo con consulta a la industria

Yazmin L. Mack-Vergara<sup>1,2,3</sup> , Nazareth Batista<sup>1,2</sup>   
y Ka Lai N. Ng Puga<sup>1,2\*</sup> 

1 Universidad Tecnológica de Panamá, Centro Experimental de Ingeniería, Grupo de Investigación Sustainable Construction UTP. Panama City, Panama.  
2 Universidad Tecnológica de Panamá, Facultad de Ingeniería Civil. Panama City, Panama.  
3 Sistema Nacional de Investigación (SNI) de Panamá. Panama City, Panama.



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\*Corresponding author:  
kalai.ng@utp.ac.pa

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### ABSTRACT

Concrete is the most widely used construction material globally and in Panama. Demand for concrete continues to increase due to population growth and housing and infrastructure development. However, its production has significant environmental impacts, associated with resource consumption, water and energy use, and greenhouse gas emissions, underscoring the need to move towards more sustainable approaches to production. In this context, the aim of this study was to propose qualification criteria for sustainable concrete production in Panama, through a participatory process integrating both academia and industry. The methodology comprised three stages: a panel of experts was recruited in order to identify preliminary criteria, a technical seminar-workshop was held to discuss these criteria, and a structured form was distributed to determine the perception of the criteria and validate them from an industry perspective. The structured form included 53 questions; 12 responses from industry representatives covering approximately 51% of Panama's concrete production were received, representing 20 plants across several provinces, ensuring high sectoral and geographical representativeness. The results indicated agreement regarding the prioritization of environmental criteria related to the reduction of CO<sub>2</sub> emissions, and the efficient use of resources, water and energy. However, participants also emphasized the need to maintain the mechanical strength of the concrete produced, in addition to the progressive incorporation of alternative materials and circular economy principles. Less agreement was apparent with regard to social aspects. Overall, this study provides a technical and consultative basis for the development of a national sustainable concrete rating system adapted to the Panamanian context.

**Keywords:** Sustainable concrete, sustainability criteria, sectoral consultation, Panama

### RESUMEN

El hormigón es el material de construcción más utilizado globalmente y en Panamá. La demanda de hormigón sigue aumentando debido al crecimiento demográfico y al desarrollo de viviendas e infraestructuras. Sin embargo, su producción tiene impactos ambientales significativos, asociados al consumo de recursos, el uso de agua y energía, y las emisiones de gases de efecto invernadero, lo que subraya la necesidad de avanzar hacia enfoques de producción más sostenibles. En este contexto, el objetivo de este estudio fue proponer criterios de calificación para la producción de hormigón sostenible en Panamá, mediante un proceso participativo que integre tanto la academia como la industria. La metodología constó de tres fases: se reclutó un panel de expertos para identificar criterios preliminares, se celebró un seminario-taller técnico para debatir estos criterios, y se distribuyó un formulario estructurado para determinar la percepción de los criterios y validarlos desde la perspectiva de la industria. El formulario estructurado incluía 53 preguntas; se recibieron 12 respuestas de representantes de la industria, que cubren aproximadamente el 51 % de la producción de hormigón en Panamá, lo que representa 20 plantas en varias provincias, para asegurar una alta representatividad sectorial y geográfica. Los resultados indicaron acuerdo respecto a la priorización de los criterios ambientales relacionados con la reducción de emisiones de CO<sub>2</sub> y el uso eficiente de recursos, agua y energía. Sin embargo, los participantes también enfatizaron la necesidad de mantener la resistencia mecánica del hormigón producido, además de la incorporación progresiva de materiales alternativos y principios de economía circular. Se observó menos acuerdo con respecto a los aspectos sociales. En conjunto, este estudio proporciona una base técnica y consultiva para el desarrollo de un sistema nacional de calificación sostenible de concreto adaptado al contexto panameño.

**Palabras clave:** hormigón sostenible, criterios de sostenibilidad, consulta sectorial, Panamá



## Introduction

Globally, concrete is an essential input for construction of the built environment and is a central component in the provision of housing and infrastructure (Elhacham *et al.*, 2020; Irassar *et al.*, 2020). Its widespread use is a consequence of its structural performance, adaptability and availability, which make it a strategic material for urban and territorial development. In Panama, its importance is intensified by the significance of the construction sector within the national economy, which in 2024 constituted approximately 17.6% of gross domestic product (CEPAL, 2025). This economic prominence, combined with population growth and high demand for housing and infrastructure, accounts for the continuity and intensification of the use of concrete in the short and medium term (Berrocal, 2020).

However, this increase in the production and consumption of concrete brings with it a series of environmental challenges that cannot be ignored (Solaimanian, 2025). The extraction and transformation of raw materials, the intensive use of natural resources, the generation of waste and the greenhouse gas emissions associated with its value chain position concrete as a key factor in any discussion regarding sustainability in the construction sector. Its impacts are particularly relevant in a context in which environmental commitments and sustainable development agendas call for structural changes to traditional production models (Comité de Alto Nivel de Seguridad Hídrica, 2016; Consejo de la Concertación Nacional para el Desarrollo, 2017; Ministerio de Ambiente, 2023).

In this scenario, the need to move towards approaches that reduce the environmental impacts of concrete, without compromising its structural function or its technical and economic feasibility, is clear (Zheng *et al.*, 2025), as expressed in the concept of sustainable concrete. When defining sustainable concrete, several studies have considered a range of aspects, but most include the incorporation of recycled aggregates and supplementary cementitious materials (SCMs) (Franco-Quiñonez *et al.*, 2025; Raman *et al.*, 2025; Ragupathi *et al.*, 2025).

The concept of sustainable concrete is associated with the characteristics of the material itself, but translating this concept into practice calls for the definition of sustainability criteria that can serve as an evaluation framework. Such criteria must allow for the environmental and operational performance of concrete mixtures or production practices to be assessed in a structured manner. Subsequently, in different contexts, these criteria may be operationalized through rating systems or certification schemes that provide the tools for appropriate implementation and comparison, across diverse projects or producers.

In Panama, the absence of clear criteria for the classification of concrete as sustainable limits the systematic adoption of practices aimed at improving its environmental performance. This hinders both the implementation of strategies at the industrial level and the design of public policies and technical specifications to promote an effective transition towards sustainable construction. It is in this context that the following research question guided this study: What does sustainable concrete mean in the Panamanian context?

Based on this question, the aim of this research was to propose qualification criteria for sustainable concrete in the Panamanian context through a participatory process integrating academia, industry and government. Through this study, it is suggested that the mechanical performance and durability of sustainable concrete should be maintained in the Panamanian context, while reducing resource, energy and water consumption, as well as CO<sub>2</sub> emissions. Furthermore, during the study shared priorities were identified, in order to guide future initiatives, regulations and strategies aligned with local conditions and specific sectoral perspectives. This study may also serve as a guide for other regions that, in common with Panama, lack locally adapted criteria, by providing a structured approach for the defining of their own criteria.

## Materials and methods

In order to enable the proposal of qualification criteria for sustainable concrete in the Panamanian context, a participatory and sequential methodology was developed in three stages. This approach was based on collaboration between academia, industry and government.

### Panel of experts

The first stage of the study consisted of a panel of experts (Pulkkinen and Simola, 2000), convened to address the question «What is a sustainable concrete in Panama?». The aim was to identify and synthesize preliminary qualification criteria from multiple perspectives. The event took place on May 9, 2025.

The event began with short presentations designed to establish a technical context and an international perspective. A research assistant student from the Technological University of Panama presented an overview of sustainable cement and concrete roadmaps, and this was followed by a presentation titled «Sustainable Concrete with Multinary Binder Systems», given by an international researcher.

Prior to the panel, a form was provided to national and international experts, consisting of research questions focused on sustainable concrete characteristics, implementation strategies, environmental indicators and public policies. This information was used to guide the panel's discussion topics.

The panel participants were invited through a purposive selection process, designed to include key actors involved in concrete production, academia and environmental governance in Panama. The final panel was composed of representatives from academia, the Panamanian Association of Concrete Producers and the Ministry of Environment, with participation from civil engineering students and the general public. A total of 40 participants attended the event.

Based on the technical dialogue, preliminary qualification criteria were formulated, combining structured consultation, technical exchange and feedback from the public, through questions and participatory dynamics.

### **Technical seminar-workshop**

The second stage was composed of a seminar-workshop (Redvall and Sørensen, 2021) titled «Qualification Criteria for Sustainable Concrete in Panama», which brought together professionals from the academic and industrial sectors, with the aim of delving into the characteristics and strategies necessary in order to move towards more environmentally responsible concrete production. The event took place on June 11, 2025.

The seminar-workshop was jointly organized by the Panamanian Association of Concrete Producers and the Technological University of Panama. A total of 20 participants attended the event, including representatives from academia, the Panamanian Association of Concrete Producers and students from the university's civil engineering department.

The findings of the panel of experts were presented during the event, and the fundamental criteria identified for the qualification of sustainable concrete were discussed. The main presentation included input from international collaborators. Also, the questions proposed for the structured form, aimed at gathering industry perspectives on the relevance and viability of the proposed criteria (third stage), were introduced and explained to the participants.

### **Structured form and sectoral consultation**

The third stage consisted of the distribution of a structured form via Microsoft Forms, the elaboration of which was based on the findings arrived at through the panel of experts and the seminar-workshop. The aim of the form was to validate the qualification criteria for sustainable concrete from an industry perspective, considering strategies, performance indicators, standards, public policies, implementation challenges and possible mechanisms to overcome such challenges.

Participation in the study was voluntary. A total of 12 participants were recruited through a purposive approach, in order to ensure adequate representation

from key actors involved in the concrete production and supply chain in Panama. Prior to completing the form, the participants were informed regarding the purpose of the study. The collected data were anonymized and used exclusively for research purposes; access to the original dataset was restricted to the principal investigator. This approach is consistent with the ethical guidelines for internet-mediated research, which state that completing a questionnaire can be considered an indicator of informed consent, provided that participants have the option to participate voluntarily and the study does not involve any significant risks (The British Psychological Society, 2021).

The form was completed by representatives of the industrial sector, covering approximately 51% of Panamanian concrete production, according to estimates based on data from the National Institute of Statistics and Census for 2022 (Instituto Nacional de Estadística y Censo, 2023). The participating companies represented 20 plants, distributed across several of Panama's provinces, thereby ensuring a high degree of geographical representativeness. Strategic actors in the value chain were included, thereby reinforcing the sectoral relevance of the results.

The form was organized into sections, with 53 questions in total. The questions were designed to capture industry perceptions regarding the viability, relevance and potential implementation challenges of the proposed sustainability criteria. The form included open-ended (text) questions, closed-ended single-choice questions, closed-ended multiple-choice questions, ranking questions, and Likert-scale questions. The complete list of questions and their corresponding types is provided in the Supplementary Material.

The responses to closed-ended questions were analyzed through descriptive interpretation of response frequencies and percentages, in order to identify levels of agreement, perceived viability and priority among the participants. Ranking questions were used to identify the relative importance assigned by participants to different sustainability characteristics. Open-ended responses were reviewed qualitatively, with the aim of identifying recurring themes related to implementation challenges, operational considerations and potential opportunities for sustainable concrete production. The results are presented together with their interpretation, in order to provide contextualization of the findings within the Panamanian concrete sector.

Based on the interpretation of the responses, the principal sustainability domains and candidate indicators identified during the consultation were synthesized into a preliminary framework.

## **Results and discussion**

To facilitate direct interpretation and contextualization of the findings, the results and discussion are presented together. The industry feedback is presented and



discussed through a structured form in the following distinct sections.

**Participant data**

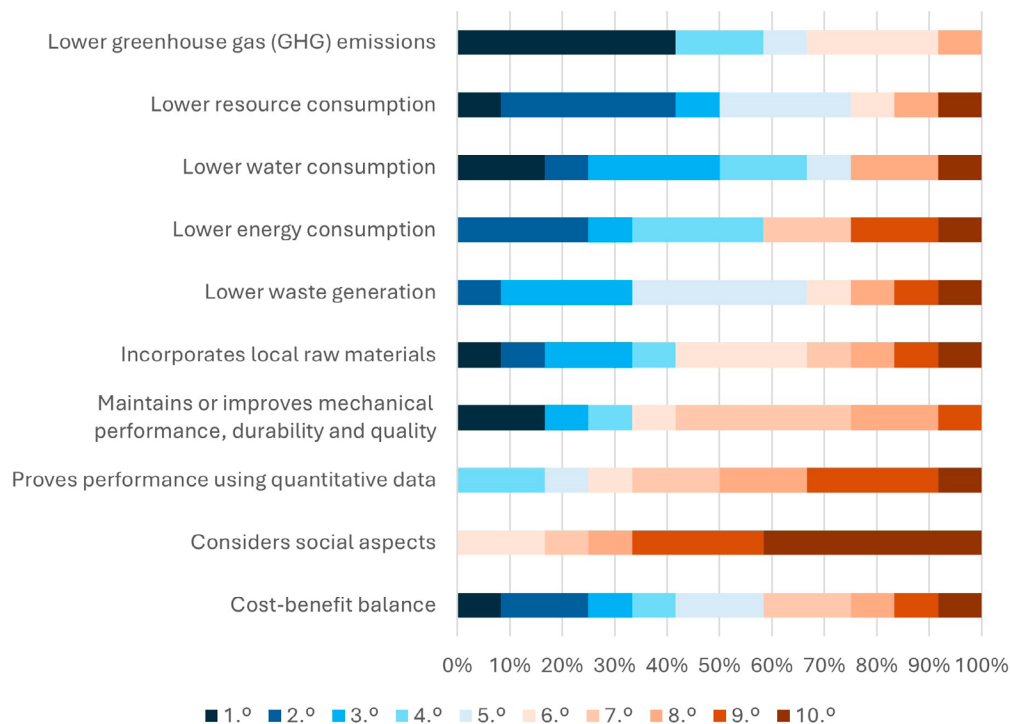
Questions 1-5 collected data from participants, while guaranteeing confidentiality. The participants were representatives of a diverse range of organizations, including one association, one laboratory, one cement supplier, and four concrete companies. In total, the group consisted of one laboratory representative and eleven industry representatives, all of whom brought expertise in the research and production of concrete. Reported areas of expertise included civil engineering, cement and concrete production, technical operations, project management, sustainability, quality control, occupational health and safety, and the environment. All the participants were involved in cement and concrete-related operations.

**Criteria consultation**

The criteria synthesized by the expert panel were prioritized by the participants, starting with the question «What are the characteristics of a sustainable concrete?» Participants ranked the ten proposed sustainability criteria for concrete from 1 (highest priority) to 10 (lowest priority). Figure 1 shows the distribution of the rankings assigned by respondents, with stacked bars representing the percentage of participants assigning each ranking position to each criterion. The participants positioned the different environmental aspects in order of priority,

led by greenhouse gas (GHG) emissions, possibly due to the actions already carried out by the cement and concrete industry in this field (GCCA, 2021; FICEM, 2025). The next highest priority for participants was resources, water and energy, which together are directly linked to a plant’s operating costs (Abushanab and Alnahhal, 2023; Martínez and Miller, 2025). Waste management and the incorporation of local raw materials were considered a medium priority. Social aspects, although mentioned by the panel of experts, were ranked last, possibly due to a lack of knowledge regarding them and how they can be measured (Mármol et al., 2023). The «Cost-benefit balance» criterion received the lowest level of agreement, with responses mostly divided over the different ranks. These findings highlight the need for a gradual integration of social aspects into sustainable concrete criteria, particularly through a linking of them with tangible issues such as occupational health, safety and community well-being. A structured roadmap for their implementation has been identified as an area for future research.

In response to the question «What other characteristics do you consider a sustainable concrete should have?», reuse and recycling were recurring terms, particularly the recycling of aggregates, which is rarely practiced in Panama and thus represents an opportunity for industry implementation. The mechanical strength of concrete was mentioned alongside environmental impacts. The need for viable public policies was also emphasized, specifically strategies, policies and other resources relevant to the industry.



**Figure 1.** Distribution of rankings assigned by participants to ten proposed sustainability criteria for concrete  
 Note. Each criterion was ranked from 1 (highest priority) to 10 (lowest priority). Stacked bars represent the percentage of respondents who assigned each ranking position.

Regarding the question «Do you consider it viable to move to project specifications based on performance-based concrete design instead of cement-type-based concrete design (I, II, III, IV and V)? and if the answer is “No”, state the reason», there was a high level of acceptance (Yes: 83%, No: 8%, Do not know: 8%) towards the performance-based approach, aligned with international trends (e.g., ACI 318) (American Concrete Institute, 2025), fib MC2020 (Bigaj-van Vliet *et al.*, 2023). However, the availability of technical data was identified as a limiting factor. This finding suggests that the transition to using performance specifications is viable, but that it requires the strengthening of technical training across national production plants and laboratories.

As for the question «Do you consider it viable to include environmental criteria within the performance criteria for concrete?», 100% answered yes. This result supports the technical and social relevance of incorporating environmental metrics into production processes.

Finally, participants were asked if they considered it viable to include social aspects within the performance criteria for concrete. If the answer was «No», they were asked to state the reason why. The responses reflect divided opinions (Yes: 50%, No: 25%, Do not know: 25%) on the incorporation of social criteria. Some participants perceived social sustainability as a topic not relevant to the material, highlighting their limited familiarity with comprehensive approaches to sustainability (Gomes Silva *et al.*, 2022). This finding suggests that the social dimension should be introduced gradually, while linking it to tangible issues such as occupational health and safety, gender perspectives and community well-being.

Furthermore, the results obtained are consistent with the industry's prioritization of the characteristics of sustainable concrete (Figure 1). Some participants noted that social aspects are not relevant currently, while others argued that concrete, as a material, should not be evaluated in terms of social criteria. Additionally, it was mentioned that the evaluation of these aspects might even interfere with the operational uses of concrete; for example, during pouring, a process that is usually time-dependent.

The results of the criteria consultation section indicate broad agreement among participants that the sustainability criteria for concrete in Panama should be based on a balance between technical performance and a reduction in environmental impacts, incorporating indicators of concrete mechanical strength; resource, water and energy consumption; and CO<sub>2</sub> emissions. Damineli *et al.* (2010) proposed the CO<sub>2</sub> intensity index to estimate the global warming potential of concrete formulations fifteen years ago. Current classification schemes are still mostly based on embodied carbon (Munro *et al.*, 2024), leaving other aspects, such as water, understudied. However, most participants consider it

viable to move towards performance-based designs and agree on the need to include environmental criteria in the evaluation of concrete. On the other hand, the social dimension continues to generate divided opinions, suggesting that progressive incorporation should be implemented and that it should be contextualized within the sector's value chain.

### Raw materials

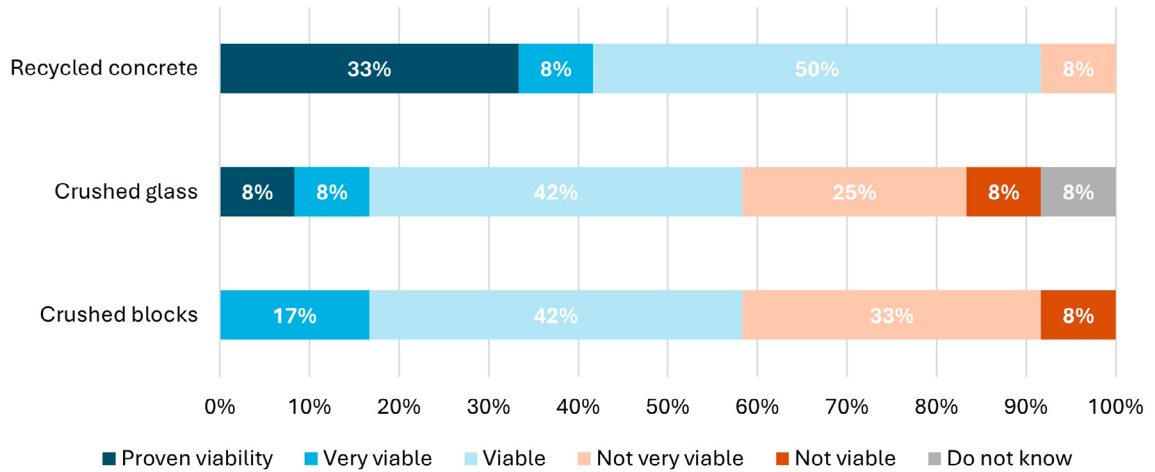
In this section, aspects related to the raw materials used in concrete production in Panama, or that have potential for such use, were evaluated. Starting with the question «Do you consider viable the incorporation of alternative aggregates in the concrete mix with a minimum established percentage? and if the answer is “No”, state the reason», there was a mostly favorable perception (Yes: 92%, Do not know: 8%) towards the incorporation of alternative aggregates. The findings suggest that this criterion can be included in the qualification of sustainable concrete, but that it should be accompanied by quality control protocols and clear regulatory limits (Müller, 2023). It will be necessary to conduct local studies on the performance and availability of these materials, given that this is a potential market.

The next question asked participants to rate the viability of incorporating the listed alternative aggregates into concrete production. Figure 2 shows the distribution of responses for each aggregate type, expressed as the percentage of respondents assigning each level of perceived viability. Recycled concrete was identified as the alternative aggregate with the greatest acceptance. This aligns with international initiatives (Kashani *et al.*, 2026) and positions recycled concrete as a priority criterion in future research and regulatory frameworks.

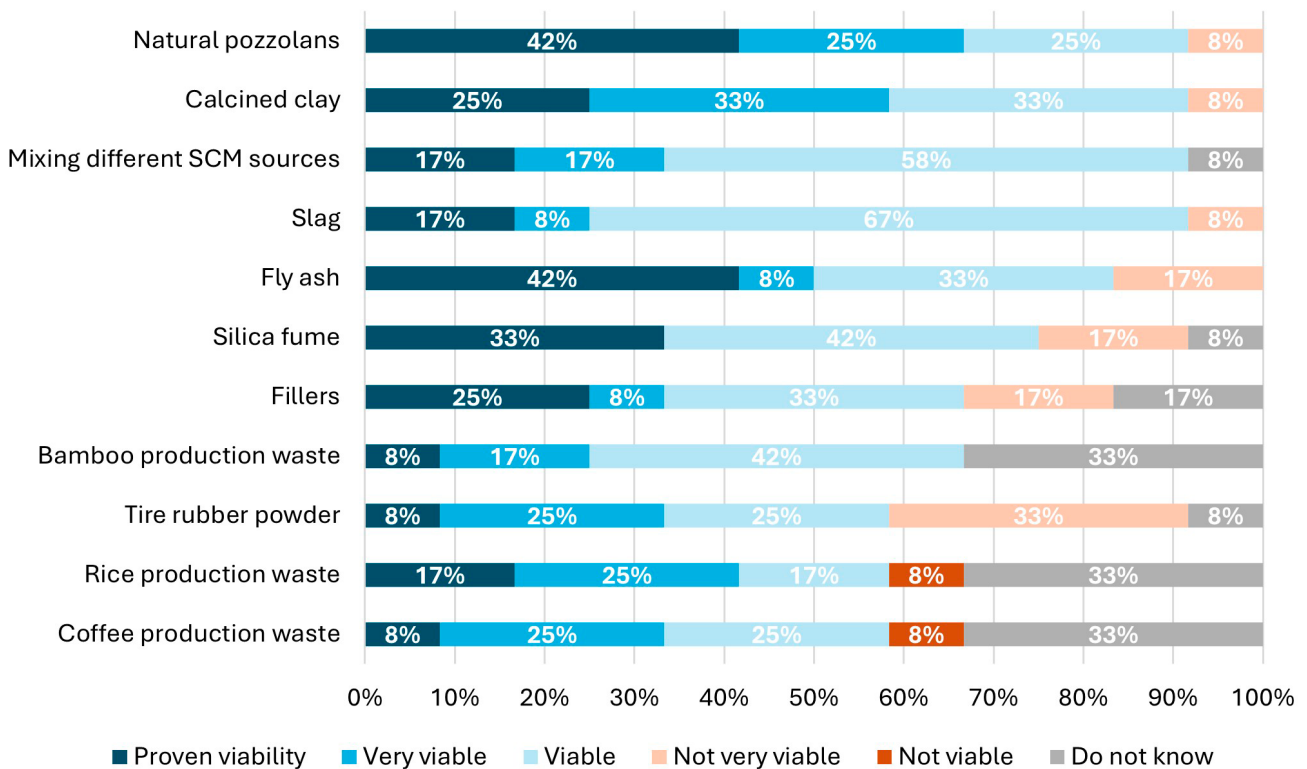
The lower acceptance of glass and crushed blocks possibly reflects concerns regarding their physical behavior and safety or participants' limited practical experience with these materials, despite ongoing research in this area (Rojas-Ramos, 2021; Domínguez *et al.*, 2022; Helmy *et al.*, 2023). These findings illustrate the relevance of including the «use of alternative aggregates» criterion, although with differentiated weighting according to the type of material.

In addition, participants were asked «What other alternative aggregates options do you consider viable in Panama?» They recognized the potential of by-products and locally sourced materials in line with the circular economy concept (Kromoser *et al.*, 2025; Nodehi and Taghvaei, 2022). The inclusion of «waste from other industries» as alternative co-products in accordance with life cycle assessment approaches (ISO, 2017) broadens the sector's vision towards resource efficiency and waste reduction, highlighting the relevance of the criteria of «lower use of resources» and «incorporation of local raw materials». Different alternatives were indicated and





**Figure 2.** Distribution of participant responses regarding the viability of incorporating alternative aggregates into concrete production in Panama  
 Note. The stacked bars show the percentage of respondents classifying each aggregate type according to its perceived viability (proven viability, very viable, viable, not very viable, not viable, or do not know).



**Figure 3.** Distribution of participants' responses regarding the viability of incorporating Supplementary Cementitious Materials (SCMs) and other mineral or waste-derived additives into concrete production in Panama  
 Note. The stacked bars show the percentage of respondents classifying each material according to its perceived viability (proven viability, very viable, viable, not very viable, not viable, or do not know).

require further investigation before being considered for use in Panama's concrete industry. In addition, it will be necessary to verify availability and economic viability, to ensure practical adoption and to differentiate between alternative aggregates (light aggregates, construction residues, basalt crushing residues, glass sand, etc.) and Supplementary Cementitious Materials (SCMs) (pozzolans, calcined clays, ashes, slags, etc.), with the

main difference being the reactivity of SCMs (Lothenbach et al., 2011).

The participants were asked whether they considered the incorporation of SCMs into concrete mix (with a minimum established percentage) as viable. If their answer was «No», they were asked to state the reason why. There was general acceptance (Yes: 92%, Do not know: 8%) for incorporating SCMs into concrete mix. However,

different alternatives will need to be investigated before their implementation, and both availability and economic feasibility should also be verified. This strategy would require modifications to concrete production plants, such as additional silos to supply SCMs to plants that do not already have them.

Participants rated the viability of incorporating the listed SCMs into concrete production. Figure 3 presents the distribution of responses for each SCM, expressed as the percentage of respondents who assigned each level of perceived viability. A broad acceptance of SCMs as partial substitutes for clinker is evident. This trend is consistent with global decarbonization strategies (GCCA, 2021; FICEM, 2025; The European Cement Association, 2020). Furthermore, this could also enable the use of «waste» from other industries, in alignment with the concept of the circular economy. Therefore, the inclusion of SCMs is generally perceived as a key and measurable criterion for sustainable concrete.

The results for SCMs from agricultural residues indicate a relatively high knowledge deficit in this area. Different alternatives were identified that should be investigated before local implementation, in order to account for regional conditions and industry practices, even if they have already been applied in other countries or have been demonstrated to be responsible for improvements in technical performance (Manan *et al.*, 2021). Other alternatives with proven viability include natural pozzolans, calcined clay, fly ash, slag and silica fume (Scrivener *et al.*, 2018). For these materials, the main challenge is local availability, given that the importing of SCMs would increase the overall carbon footprint.

Although the mixing of different SCMs sources was rated as viable, implementing this method could present logistical and technical challenges. In other countries, use of these mixtures has required advanced technical knowledge, and even the use of artificial intelligence, in order to analyze the results of different mixes in accordance with the SCMs available in a specific region (Arvizu-Montes *et al.*, 2025; Parhi and Patro, 2025). Therefore, verification would be required of the availability and economic feasibility in the context of the Panamanian market. With regard to local availability, it is recommended that the use of fillers and calcined clay be considered.

When they were asked about other SCMs options, biomass ash (Wu *et al.*, 2025), ground glass (Helmy *et al.*, 2023), and crushed basalt (Sharaky *et al.*, 2022) were identified by the participants as alternative SCMs in the Panamanian context. These options offer significant potential in terms of the reduction of clinker consumption and the emissions associated with cement production, while at the same time promoting the valorization of industrial waste and local by-products. Their use could strengthen the circular economy within the sector,

provided that additional characterization, reactivity and mechanical performance studies are conducted out, along with availability and economic feasibility assessments, in order to support their gradual incorporation into sustainable concrete mixtures.

With regard to regulations, the participants were asked if they thought that establishing a minimum mandatory use of Supplementary Cementitious Materials (SCMs) as part of a regulatory framework for concrete production would negatively impact their operations. They were asked to state the reason for both yes and no answers. The answers were divided almost 50/50 (Yes: 50%, No: 42%, Do not know: 8%).

These responses point to concerns regarding logistical and regulatory challenges, particularly in terms of the availability and certification of local SCMs. The costs of material and their handling and storage were also identified as a concern, in a concrete market where competitiveness is primarily based on price; any additional costs can affect sales. In most cases, the producer must bear these costs, rather than reducing their competitiveness—which is not always possible given the sector's low profit margins—or incorporate them into the product's price, making them particularly vulnerable to market fluctuations. However, general recognition of the positive impact on sustainability suggests that adoption should be gradual, supported by regulatory incentives and technical support. This finding supports the inclusion of the criterion, but not with immediate effect.

With regard to the circular economy criterion (Kromoser *et al.*, 2025; Nodehi and Taghvaei, 2022), participants were asked if they considered partnering with other producers and consumers to implement a circular economy as viable. If the answer was «No», they were asked to state the reason why. There was a high level of agreement (Yes: 92%, Do not know: 8%) on the need for collaboration between producers, consumers and institutions, in order to close material cycles. This result supports the circular economy criterion as an essential sustainability component in the Panamanian concrete industry and highlights the potential opportunity to explore this aspect.

Finally, the participants were asked if they agreed with minimizing the production and use of bagged cement. If they answered «No», they were asked to state the reason why. The answers were divided almost 50/50 (Yes: 42%, No: 50%, Do not know: 8%).

Reducing the production and use of bagged cement is proposed based on the fact that this practice generates a greater amount of waste and offers low operational efficiency, given that a significant percentage of the material remains in the bag or is lost or degraded by exposure to the open air. Also, bags cannot always be fully used, due to adherence to required concrete volumes. Bagged cement is difficult to preserve because, as a



hydraulic material highly reactive to moisture, its useful life is considerably reduced in uncontrolled environmental conditions.

Support for this measure reflects a growing awareness of logistics efficiency and waste reduction issues. However, the opposite response suggests that there still exist niche markets or operational contexts where their use is unavoidable. Taken together, the responses suggest that promoting bulk over bagged cement, considering the scale of operation and infrastructure availability, is a relevant criterion.

The results of this section demonstrate that the sector feels positively towards the transition to sustainable practices, while emphasizing the need for a gradual incorporation of alternative aggregates and SCMs (Ali *et al.*, 2025). Also apparent is the call for a circular economy and the economic incentives required to balance out the additional investment needed (Morrison *et al.*, 2025). The high level of agreement on these questions validates the preliminary structure of the criteria for rating sustainable concrete in Panama and its technical relevance and alignment with international decarbonization strategies for the cement-concrete sector (GCCA, 2021; FICEM, 2025; The European Cement Association, 2020).

**Water**

In this section, aspects related to the use, or potential use, of water in concrete production in Panama, where water resources are an important concern (Larsen, 2019), were evaluated. Initially, the participants were asked whether they considered viable the measuring and monitoring of water sources at concrete production plants. If the answer was «No», they were asked to state the reason why.

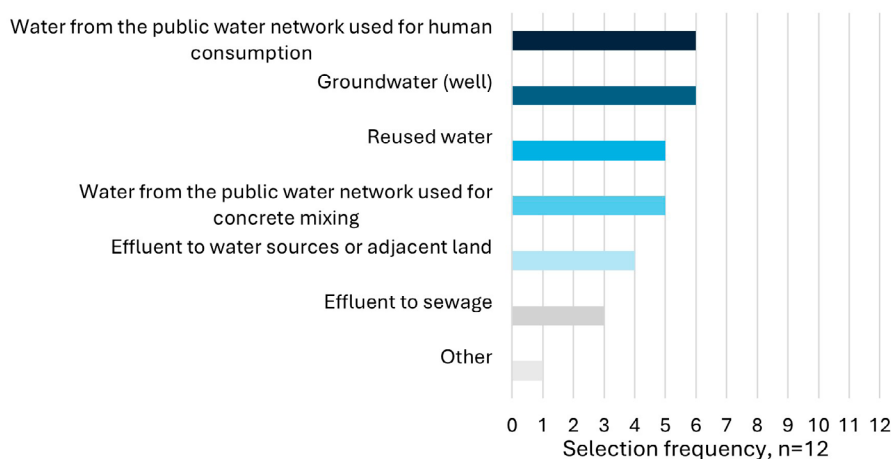
There was 100% consensus on the importance and viability of monitoring water sources, demonstrating that water control in Panamanian concrete plants is achievable.

This result supports the proposal for the incorporation of an indicator for the management and monitoring of water consumption, which is essential for measuring water efficiency and operational sustainability, as recommended by Mack-Vergara *et al.* (2025). Furthermore, this would require monitoring and mechanisms to control abstraction rates, prioritize human consumption, and ensure that groundwater use and rainwater harvesting do not compromise local water availability or ecological flow requirements.

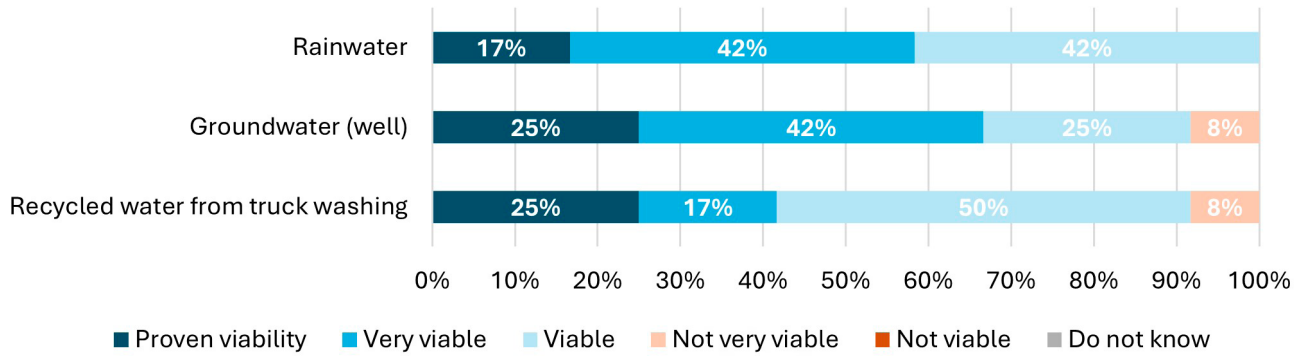
The participants were asked whether they implemented water-recycling practices during concrete production (Yes: 83%, No: 8%, Do not know: 8%). If their answer was «No», they were asked whether they considered it to be viable, to which 100% responded that it was.

Most companies already implement washing and process water recycling, demonstrating progress in circular resource management. These practices have been validated in international studies (Ekolu and Dawneerangen, 2010; Tsimas and Zervaki, 2011). Negative responses were accompanied by a willingness to implement these practices, suggesting technical viability and sectoral acceptance. This finding suggests that water reuse within the production process is an important component of sustainable concrete. The participants were asked if they implemented rainwater harvesting during concrete production (Yes: 67%, No: 17%, Do not know: 17%). If the answer was «No», they were asked whether they considered it to be viable, to which 100% responded that it was.

These responses indicate that several plants already practice rainwater harvesting, and that those which do not consider it to be viable. In other countries, this practice is already widespread as a water security measure (Barrios, 2023). The responses, therefore, suggest that rainwater use could be considered as an indicator of alternative water sources, which is particularly relevant in a high-rainfall region like Panama (The World Bank Group, 2024).



**Figure 4.** Water flows in concrete production plants for which participants reported quality monitoring practices  
 Note. The bars represent the number of respondents who identified each monitored water flow.



**Figure 5.** Industry assessment of the viability of using alternative water sources in concrete mix

Participants were asked whether they conducted water quality monitoring in concrete production plants (Yes: 75%, Do not know: 25%). If the answer was «Yes», they were asked to state in which water flows the quality is monitored, by selecting all the applicable options from the list provided. Figure 4 shows the number of respondents who selected each water source.

Judging from the participants' responses, it appears that water quality monitoring is widely practiced, thereby ensuring compliance with DGNTI-COPANIT (Ministerio de Comercio e Industrias, 2000a, 2000b, 2000c) and ASTM C1602 (American Society for Testing and Materials, 2018) technical standards. This result supports consideration of the water used in production as a basic condition for the sustainability and durability of concrete as a quality control criterion (Belur Raju *et al.*, 2025). On a smaller scale, effluent monitoring was also indicated. These findings highlight the importance of strengthening water quality monitoring practices, including effluent control, and aligning them with existing standards, while ensuring the identification of which parameters are measured and which parameters should be measured.

The viability of using alternative water sources (i.e., other than water from the public network—Instituto Nacional de Acueductos y Alcantarillados Nacionales - IDAAN) in the concrete mix was rated by the participants (Figure 5), who were also asked to indicate other alternative water sources they considered viable for concrete production in Panama.

The responses indicate a high acceptance of alternative sources, with priority given to treated and recycled water (Figure 5). Quarry water is mentioned; however, its use is recommended only at the quarry site, as transporting water to concrete plants from these locations could increase costs and GHG emissions, unless the quarry is adjacent to the concrete production plant or there is extreme water scarcity. These responses support diversifying water sources as a sustainable practice, helping reduce dependence and pressure on the public supply system and improving the sector's overall water resilience.

Continuing with the theme of water considerations, the participants were asked if they thought that establishing restrictions regarding the supply of water from the IDAAN in concrete production would negatively impact their operations (Yes: 83%, No: 8%, Do not know: 8%). If the answer was «Yes», they were asked to state how their operation would be impacted.

The challenges identified included costs, dependence upon drinking water as the primary raw material in concrete production, customer specifications for water quality, and the limited availability of alternative sources. This finding reinforces the need to promote applied research and pilot demonstrations on the use of alternative water sources in concrete mixing and related processes, supporting this criterion as an opportunity for innovation and continuous improvement.

While acknowledging the dependence upon water from the public network, some participants pointed out that restrictions could drive greater efficiency and internal reuse. This result highlights the importance of reducing dependence upon potable water sources and strengthening plant water autonomy. These findings suggest the need to progressively incorporate quantitative indicators, such as the reduction of dependence upon potable water sources and the implementation of rainwater harvesting systems, which is of particular relevance in a high-rainfall context like that of Panama.

Finally, the participants were asked whether increasing the cost of water supply from the public network for concrete production would negatively impact their operations (Yes: 67%, No: 8%, Do not know: 25%). If the answer was «Yes», they were asked to state how their operations would be impacted.

Most of the participants expressed the belief that an increase in water costs from the public network would negatively impact their operations. Although this could be an indirect incentive to improve water efficiency, it raises concerns about the competitiveness of their product (concrete). This finding illustrates the importance of economic and efficiency indicators. These

findings also suggest a potential role for economic incentives to support plants that achieve high levels of water efficiency or implement alternative water sources, thus helping to balance environmental performance with economic competitiveness. Such incentives could include preferential scoring in public procurement processes for suppliers demonstrating high water efficiency, for instance.

The results of this section reflect a high level of agreement regarding the relevance of sustainable water management in concrete production, aligned with the latest research (Sheikh Hassani *et al.*, 2023; Thombare *et al.*, 2026). Most plants already implement recycling, monitoring and rainwater harvesting practices, demonstrating both the technical viability and institutional interest in optimizing resource use, as has been demonstrated in other regions (Yousuf *et al.*, 2023). The criteria associated with water efficiency, monitoring, use of alternative sources and water quality control are perceived as fundamental elements of the sustainable concrete qualification system. However, concern regarding the economic impacts linked to the cost or restriction of water underscore the need for support mechanisms and public policies to facilitate the transition towards more responsible and competitive water management (Zhang and Oki, 2023).

**Energy and CO<sub>2</sub> emissions**

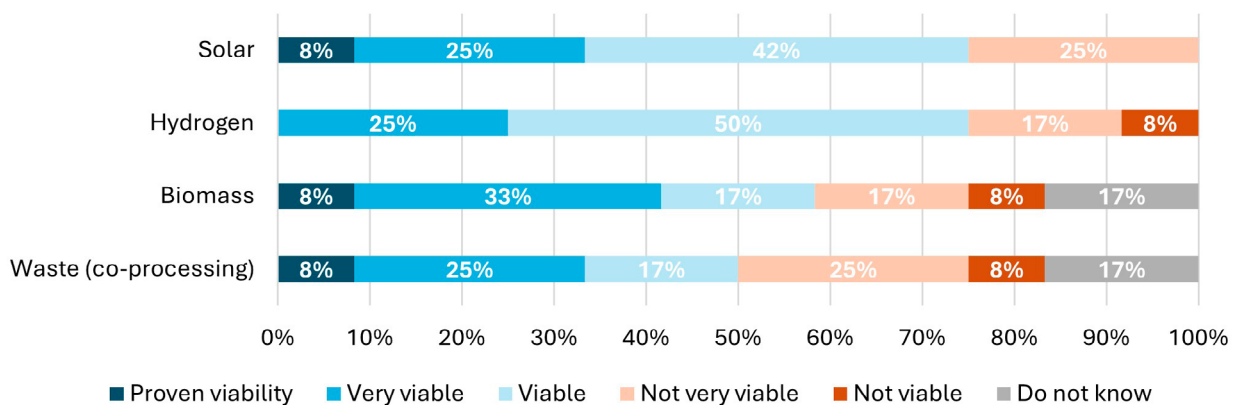
In this section, aspects related to energy sources –or potential sources– and emissions resulting from the production of concrete in Panama were evaluated. Concrete production is usually identified as energy –and CO<sub>2</sub>– intensive, although much of this is due to cement production (Sbahieh *et al.*, 2025). An important aspect in concrete production is transportation; therefore, the first question posed was «Do you consider the transition to electric or hybrid vehicles and equipment viable in concrete production in Panama?» (Yes: 50%, No: 17%, Do not know: 33%). If the answer was «No», participants were asked to state the reason why.

The responses indicate a divided perception of the viability of transitioning to electric or hybrid vehicles and equipment for concrete production in Panama. These technologies have already been studied and implemented in other regions (Yang *et al.*, 2023). Half of the participants considered the transition viable, while 17% did not consider it viable, and 33% expressed uncertainty. Among the negative responses, the potential associated costs were identified as the main limitation. In addition, participants were requested to rate the viability of using alternative energy sources in concrete production (Figure 6).

The findings pertaining to hydrogen and solar illustrate the high potential for energy diversification in Panama’s concrete industry (Deago *et al.*, 2022; Boya-Lara, 2025). These options are perceived as viable in the short and medium term, while waste co-processing and biomass are seen as emerging alternatives with medium viability. This result suggests that the criterion of use of renewable energies and co-processing of waste should be included within the rating system, in keeping with the decarbonization strategies promoted by GCCA (2021) and FICEM (2025); however, there is often no recognition of alternative energy sources, indicating a failure to promote such practices.

As for other alternative energy sources considered viable for concrete production in Panama, the limited identification of these alternatives reflects the sector’s current dependence upon fossil fuels and limited local experience with emerging energy sources. This finding reinforces the need to promote applied research and introduce pilot demonstrations focused on renewable energies in concrete plants, underscoring the importance of this criterion as an opportunity for innovation and continuous improvement.

It is important to differentiate between clinker and cement production, which is conducted over relatively large areas where co-processing and other processes can be implemented, from concrete production, which is carried out in smaller areas. This means that any use of alternative energy sources would be restricted by the



**Figure 6.** Industry assessment of the viability of using alternative energy sources in concrete production

area required versus the area available, where energy is produced locally. However, there are alternative-energy-based electricity providers that produce energy at a location other than the concrete production plant. These providers are already used by some companies, although recognition of these efforts is limited in Panama.

There is a company in Panama that injects CO<sub>2</sub> into the concrete mix (Alia Concretos Panamá, 2026), and therefore the viability of this practice for carbon capture in Panama was also evaluated (Yes: 50%, No: 33%, Do not know: 17%). If the answer was «No», participants were asked to state the reason why.

The use of CO<sub>2</sub> injection for carbon capturing was met with divided opinions in terms of its viability in Panama. Economic barriers were presented as the main challenge, as any additional cost is perceived as problematic in what is a highly competitive and cost-sensitive market. Possible durability problems were also alluded to, together with uncertainty as to the origin of the injected CO<sub>2</sub>. This finding reinforces the need to promote applied research and pilot demonstrations on CO<sub>2</sub> capture in concrete, and the significance of this criterion as an opportunity for innovation. The innovation criterion for emission reduction is therefore considered relevant; however, its implementation will require technological maturity, knowledge transfer and institutional support.

In Panama, there are two concrete production plants that inject CO<sub>2</sub> (Lima *et al.*, 2025). One of these plants was visited, and the operators reported that the mechanical strength of the concrete is not affected and that, in fact, in some cases it is increased. As for costs, since they

conduct this practice within an internationally recognized program, these are covered, and the company indicated that there is no increase in concrete costs, and that, therefore, they remain competitive.

The results in this section indicate that energy transition and emission reductions are recognized as strategic priorities, but that there are economic and technological barriers in developing countries (Falcone, 2023). There is agreement on the viability of solar energy and hydrogen, and moderate acceptance of co-processing and biomass as complementary alternatives (Falcone, 2023). In contrast, the electrification of machinery (Un-Noor *et al.*, 2022) and CO<sub>2</sub> injection (Davolio *et al.*, 2025) continue to be perceived as long-term initiatives, despite the success stories documented in the country. Overall, the findings underscore the relevance of including criteria related to energy efficiency, use of renewable energies and emission mitigation in the rating system for sustainable concrete, while ensuring realistic and progressive approaches adapted to the Panamanian context, combined with supportive public policies, recognition and economic incentives to compensate for the required investment.

### **Sustainability criteria for concrete production in Panama**

Based on the consultation results, a preliminary framework of sustainability criteria for concrete production in Panama was constructed. This framework features the main domains identified in the consultation, potential indicators, their rationale, the level of agreement among participants, and areas requiring further research or other actions, prior to broader implementation (Table 1).

**Table 1.** Preliminary framework of sustainability criteria for concrete production in Panama based on a sector consultation

Domain	Indicator	Rationale	Level of agreement among participants	Research or actions needed before broader adoption
Technical performance	Mechanical strength and durability	Ensures that sustainability measures do not compromise structural performance or lifespan	High	Use of performance-based specifications and strengthening of national testing capacity
Climate impact	CO <sub>2</sub> emissions	Identified as the highest priority criterion by participants	High	Development of benchmarks and metrics for carbon intensity of concrete
Resource efficiency	Resources consumption	Supports efficient use of natural resources and optimized mix designs	High	Life cycle assessment studies adapted to the Panamanian context
Raw materials	Incorporation of Supplementary Cementitious Materials (SCMs)	Reduces clinker consumption and associated emissions	High	Local studies on material availability, performance, quality control and economic feasibility
Circular economy	Partnerships across the value chain	Enables the use of by-products and material circularity	High	Development of supply chains and regulatory incentives
Water management	Quality, recycling and reuse of water	Improves water efficiency and operational control in production plants	High	Standardized monitoring indicators and operational guidelines
Raw materials	Use of alternative aggregates	Reduces extraction of virgin materials and promotes circular use of construction waste	Moderate-high	Local studies on material availability, performance, quality control and economic feasibility
Water management	Use of alternative water sources	Reduces pressure on potable water supply	Moderate-high	Research on quality parameters and regulatory standards
Energy transition	Use of renewable energy sources	Contributes to the decarbonization of concrete production	Moderate	Economic feasibility studies and policy incentives
Social dimension	Occupational safety, gender perspectives and community well-being aspects	Emerging sustainability dimension with limited sector familiarity	Low-moderate	Development of measurable indicators and sector awareness

This framework summarizes the main sustainability domains and candidate indicators identified through the consultation process and highlights areas where further research or sectoral coordination may be needed, prior to broader implementation.

## Conclusions

The sustainability of concrete, while preserving its mechanical performance and durability, accompanied by reductions in resource, energy and water consumption and CO<sub>2</sub> emissions, is perceived as relevant in the Panamanian context. These elements form the basis of a rating system.

Most of the participants considered it viable to adopt designs in accordance with performance and measurable environmental criteria, provided that technical capabilities and testing infrastructure are strengthened at the national level.

Greenhouse gas (GHG) emissions were identified as the top environmental priority, followed by resource use, water and energy. Environmental aspects, energy efficiency, carbon and water footprints, and the use of local raw materials are therefore recognized as essential pillars of sustainability in concrete production, supporting their inclusion in the qualification criteria.

Within the sector, both the understanding and application of social aspects remain limited; however, there is a willingness to gradually incorporate these aspects, through linking them to occupational health and safety, gender perspectives and community welfare.

There is general acceptance of alternative aggregates and SCMs, provided their incorporation is progressive and accompanied by technical and quality validation. Most Supplementary Cementitious Materials (SCMs) were considered viable, with natural pozzolans rated highest. The circular economy is also recognized as a key pillar of concrete sustainability, with recycled concrete perceived as the most viable alternative aggregate.

Public network water and groundwater were the most commonly monitored sources, while rainwater was seen as the most viable alternative. The importance of including indicators on water monitoring, water recycling, rainwater harvesting and diversification of water sources

is supported by the results. Most plants already apply best practices, demonstrating the technical viability of the proposed water criteria.

The participants recognized the need for energy transition to prioritize solar energy, waste co-processing and operational efficiency. Solar energy was considered the most viable alternative energy source, followed by hydrogen. However, there remain economic and technological barriers to electrification and CO<sub>2</sub> capture, indicating the need for a phased approach and reaffirming that sustainability in concrete production in Panama will require a gradual but decisive transition.

## Authors' contributions

Yazmin L. Mack-Vergara: Conceptualization, methodology, validation, formal analysis, investigation, resources, writing (original draft, writing), revising and editing, supervision, project administration, funding acquisition.

Nazareth Batista: Validation, investigation, resources, data curation, writing (revising and editing), visualization.

Ka Lai N. Ng Puga: Validation, investigation, resources, data curation, writing (revising and editing), supervision.

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## Conflicts of interest

The authors declare no conflicts of interest.

## Artificial intelligence declaration

Grammarly and ChatGPT were used solely for language editing and clarity. The authors remain fully responsible for the content, analysis and conclusions of this work.

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