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Between green and gray: decarbonization of Portland cement and durability of concrete – a critical review.

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ABSTRACT

This paper presents a critical review of the decarbonization of Portland cement (PC) and its implications for concrete durability. The reduction of clinker content, a central strategy to mitigate CO_2 emissions, has been accompanied by physicochemical adjustments that increase PC reactivity, leading to higher heat of hydration and a greater risk of expansive reactions. Moreover, the lower alkaline reserve of low-carbon cement accelerates carbonation, increasing the probability of steel reinforcement corrosion. These and other issues must be considered in the decarbonization process, highlighting the need for systemic studies that address the trade-offs between CO_2 reduction and long-term durability over the service life of concrete structures.

Keywords: low-emission cements, durability performance, service life, climate change.

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Entre el verde y el gris: descarbonización del cemento Portland y la durabilidad del hormigón – una revisión crítica.

RESUMEN

Este artículo presenta una revisión crítica de la descarbonización del cemento Portland (CP) y sus implicaciones para la durabilidad del hormigón. La reducción del contenido de clínker, estrategia central para mitigar las emisiones de CO_2, ha sido acompañada de ajustes fisicoquímicos que aumentan la reactividad del CP, elevando el calor de hidratación y el riesgo de reacciones expansivas. Además, la menor reserva alcalina de los cementos de menor emisión acelera la carbonatación, lo que aumenta la probabilidad de corrosión de las armaduras. Estas y otras cuestiones deben considerarse en el proceso de descarbonización, lo que evidencia la necesidad de estudios sistémicos que aborden las compensaciones entre la reducción de CO_2 y la durabilidad a lo largo de la vida útil de las estructuras de hormigón.

Palabras clave: cementos de baja emisividad; durabilidad; vida útil; cambio climático.

Entre o verde e o cinza: descarbonização do cimento Portland e durabilidade do concreto – uma revisão crítica.

RESUMO

Este artigo apresenta uma revisão crítica sobre a descarbonização do cimento Portland (CP) e suas implicações para a durabilidade do concreto. A redução do teor de clínquer, estratégia central para mitigar as emissões de CO_2, tem sido acompanhada por alterações físico-químicas que elevam a reatividade do CP, aumentando o calor de hidratação e o risco de reações expansivas. Ademais, a menor reserva alcalina acelera a carbonatação, elevando o risco de corrosão das armaduras. Estas e outras questões devem ser consideradas no processo de descarbonização, sendo necessários estudos sistêmicos que abordem as compensações entre a redução de CO_2 e a durabilidade ao longo do ciclo de vida das estruturas de concreto.

Palavras-chave: cimentos menos emissivos; desempenho de durabilidade, vida útil, mudanças climáticas.

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1. INTRODUCTION

Industrialization, which began in the 18th century, brought numerous advances to humanity, including the development of Portland cement, which has since become one of the primary construction materials. However, this process also triggered significant and long-lasting environmental impacts. Atmospheric carbon concentrations have increased exponentially, rising from 280 ppm in 1800 to 428 ppm in 2025 (NOAA, 2025), causing significant and undesirable climate changes, such as global warming, a phenomenon directly associated with atmospheric carbon concentrations. In parallel, from 1800 to 2025, the global population grew from approximately 1 billion to 8.1 billion (Population Matters, 2025). It is estimated that by 2050, Earth will have 9.8 billion inhabitants (United Nations, 2017), with increasing demands for everything from food to construction materials, items essential for human survival.

This demographic expansion intensifies pressure on natural resources, especially regarding the expansion and adaptation of the built environment. The built environment comprises housing (houses, apartments), supporting and leisure infrastructure (hospitals, daycare centers, schools, parks, malls, clubs, etc.), production facilities (industries, stores, distribution centers), and mobility (roads, airports, ports, waterways, etc.), among others. Consequently, the effective demand for material resources tends to grow intensively as the population increases. Under current production and consumption patterns (business as usual), this is directly associated with energy consumption and carbon emissions.

Among the critical materials in this process, Portland cement (PC) stands out as the primary reactive component of concrete, one of the most consumed materials in the world, with a global average of 563 kg per inhabitant per year (Kumar, 2020). This figure is expected to rise due to population growth and demands for urban and housing infrastructure. The environmental problem of Portland cement stems from its high consumption, which, in turn, leads to high CO_2 emissions associated with its production (Habert et al., 2020; Olivier & Paters, 2020; Rissman et al., 2020). For the manufacture of one ton of clinker, 850 to 1000 kg of CO_2 are emitted (Habert & Roussel, 2009; Possan, 2019), with 60–65% of the carbon originating from chemical sources, resulting from the decarbonation of limestone during the clinkering process, and 30–40% resulting from the use of fossil fuels (Adesina, 2020; Possan, 2019; ROADMAP BRASIL, 2019a). These indicators, associated with high PC consumption, make the cement industry responsible for 5–8% of global CO_2 emissions (Hansen et al., 2023; IPPC, 1992), highlighting its importance in the fight against climate change. To achieve net-zero emissions by 2050, as sought by the Paris Agreement (United Nations, 2015), the gradual implementation of a set of actions is necessary. These are associated both with the PC production process, such as energy efficiency, the use of renewable fuels, and carbon capture, and with the material itself, such as increasing clinker reactivity through physicochemical processes. These processes allow a reduction in clinker content in cement and the use of higher levels of supplementary cementitious materials (SCMs) and fillers.

In this regard, various roadmaps have been published by global cement industry associations (IEA/CSI, 2009; ROADMAP BRASIL, 2019a; WBCSD, 2018b), presenting the action plans necessary over the years to decarbonize Portland cement. The first actions implemented, or in the implementation stage, focus mainly on emission reduction, centering on energy efficiency, fuel switching, and reducing clinker content in cement, which have lower implementation costs. More significant actions fall within the scope of carbon removal. They are scheduled for implementation starting in 2030, including CCUS (Carbon Capture, Utilization, and Storage) technologies, which are still in development and require high upfront costs. CCUS techniques are considered essential for global decarbonization (Coffetti et al., 2022; Emanuelsson et al., 2025; S. Kumar et al., 2025; Nehdi et al., 2024), becoming solutions of interest in the carbon market, which is currently in effect in just over 20 countries, mainly in the European Union (Dolphin and Merkle, 2025), and was

recently implemented in Brazil by Law 15.042 in December 2024 (Brasil, 2024).
Regarding ongoing actions aimed at PC decarbonization, this article will address only the aspects of the strategy to reduce clinker content in Portland cement to promote CO_2 emission reductions in the cement sector and evaluate the effects on the durability of concrete structures produced with lower-emission cements. To implement this strategy, Habert et al. (2020), Kumar et al. (2025) e Juenger et al. (2019) highlight that reactive or inert supplementary cementitious materials (SCMs) are currently used as clinker replacements, primarily fly ash, blast furnace slag, calcined clays, and limestone filler.
The first two products are reactive waste materials from thermoelectric power plants and steel mills, respectively, and are considered carbon neutral. According to Scrivener et al. (2018), these materials are produced in insufficient volumes to meet production scale, with availability limited to the generating supply chain. The use of calcined clays and fillers has gained prominence due to raw material availability; despite the demand for calcination (clay) and grinding (filler and clay), these processes result in lower CO_2 emissions than Portland clinker, constituting a potential alternative for the decarbonization of the cement sector.
Fillers have stood out in this scenario because they depend only on extraction and grinding processes, making them less emissive and cheaper than PC (Scrivener, et al, 2018). As they are inert materials, in applications within non-packed matrices and without additives, fillers do not contribute to the chemical reactions of PC or to the increase in mechanical strength of cement-based materials over time (Oliveira et al., 2023). Therefore, without the association of particle packing and the use of dispersing agents, the incorporation of higher filler contents, as well as higher SCM contents, may require the industry to promote physicochemical changes to increase the reactivity of both the clinker and the Portland cement.
The increase in cement reactivity, even after dilution with SCMs as a clinker replacement, has implications for the heat of hydration. This raises the risk of pathological manifestations, especially thermal cracking, which appears at early ages, and favors DEF (Delayed Ettringite Formation) observed at later ages under specific conditions.
Thus, evaluating how the decarbonization of PC may affect the durability of concrete structures constitutes a research topic worth exploring, as the literature on the subject is sparse. Therefore, this paper presents a critical review of recent studies and sectoral initiatives, focusing on the main decarbonization routes for the cement industry, particularly the reduction of the clinker factor using supplementary cementitious materials (SCMs). The article analyzes the current decarbonization process for Portland cement (PC) and questions its potential implications for the durability of concrete structures.

2. DEVELOPMENT AND CARBON EMISSIONS

Homo sapiens, over millions of years, has discovered, refined, and applied various technologies that have led to the current stage of development. Humanity has developed a set of technologies on a global scale that have brought about significant social, cultural, and environmental transformations. Along this path, a trajectory is observed ranging from the development of language 6 million years ago to genetic engineering and generative artificial intelligence in modern times (Figure 1). During this interval, stone tools were developed, along with the mastery of fire, agriculture, writing, the printing press, the internal combustion engine, and the internet, among other technologies.

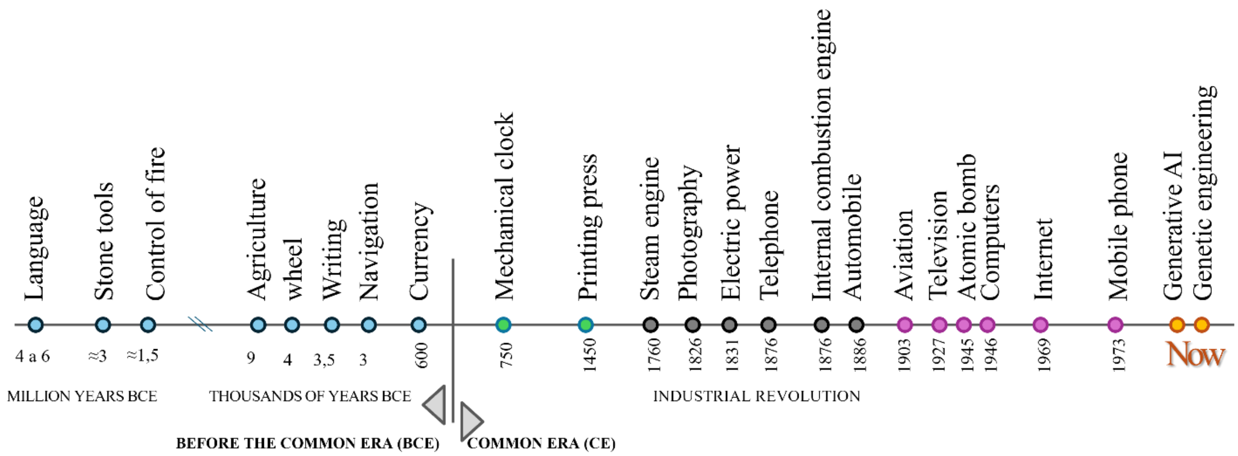

Figure 1. World-order Technologies that changed the world (adapted from Harari, 2020, 2024; Suleyman & Bhaskar, 2023).

The period following the Industrial Revolution saw the most significant number of transformative discoveries, primarily driven by the increased availability of energy, which enabled broad technological development. However, this extensive development, based on an energy system powered by fossil fuels, primarily coal and oil, and the extraction of non-renewable natural resources to meet a demand for consumption far beyond human subsistence, has led to an exponential rise in carbon emissions and population growth (Figure 2).

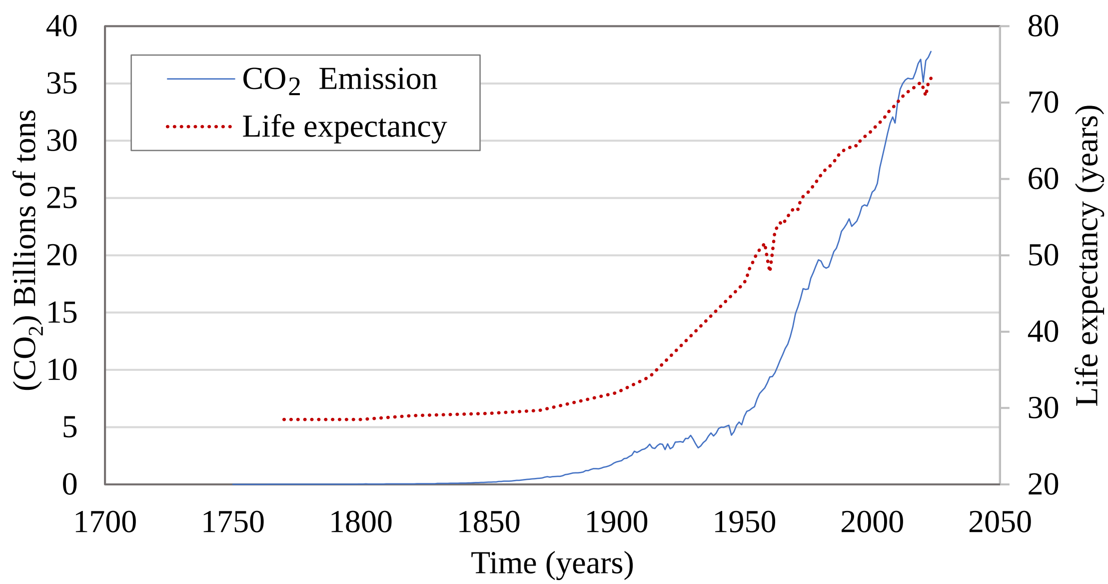

Figure 2. Global CO_2 emissions (Ritchie & Roser, 2025) and life expectancy (Dattani et al., 2025) from Industrial Revolution to the present.

Scientists worldwide have associated global warming with increases in atmospheric CO_2 concentrations. Although global warming is a natural cycle, the current era witnesses a unique and alarming acceleration, with records exceeding those of previous epochs. In less than 200 years, human activities have increased atmospheric CO_2 content by 50% (NASA, 2025). Currently, the average global atmospheric CO2 concentration is at its highest recorded value in millions of years (NASA, 2025). Under the current global geopolitical approach to GHG emissions, global warming will exceed 1.5°C in the 2020s and 2°C before 2050 (Hansen et al., 2023).
Conversely, these developments have contributed to a rise in life expectancy, from 29 years

between 1770 and 1870 to approximately 50 and 73 years in 1950 and 2023, respectively (Dattani et al., 2025). The increase in life expectancy is associated with improvements in living conditions, including access to food, heating, medicine, and vaccines (OECD, 2024). According to historian Harari (2020), genetic engineering within this century could significantly increase human longevity, especially for those with access to preventive healthcare.

However, these long-lived individuals will need a living planet! Current scenarios are not optimistic.

Compared to the pre-industrial era, global warming has resulted in fewer "outdoor days" (Choi et al., 2024), the melting of polar ice caps and rising sea levels (Koutroulis, 2019), and an increase in the intensity of rainfall and extreme events, such as the one that struck the city of Porto Alegre, Brazil, in 2024, among other factors associated with climate change. In 2024, the planet exceeded the IPCC's optimistic goal of limiting the temperature rise to 1.5°C by 2030 relative to the pre-industrial era (NOAA/ESRL, 2025). In 2025, the U.S. – one of the world's largest polluters – withdrew from the Paris Agreement (a global accord to mitigate the effects of global warming). Furthermore, the world seems to be on the verge of new armed conflicts, actions that delay the carbon containment process that humanity urgently needs to promote. This is the scenario of 2025.

Population growth and global development trends are expected to intensify demand for cement, thereby expanding CO_2 emissions from a sector that already ranks among the hardest to decarbonize (Olsson et al., 2023; Shah et al., 2022). The central question today is how to continue human development while simultaneously achieving the carbon containment necessary to halt or minimize global warming, ensuring the continuity of life as we know it on Earth. Technical optimists believe that some technology will be developed to save us! While this remains a utopia, humanity is left to hope for a collective judgment in favor of the Earth.

In this context, the construction industry will be called upon to respond to two seemingly incompatible human needs: preserving the environment, supporting population growth by providing housing and infrastructure, and facilitating reconstruction in conflict-affected regions. Because Portland cement is one of the most widely used construction materials, it holds particular importance in the decarbonization process and is the focus of this paper.

3. CEMENT, CONCRETE AND DURABILITY

Cement and concrete are milestones of contemporary development. They are noteworthy for their versatile applications in the production of cementitious materials such as pastes, mortars, and concretes, which can be produced anywhere by the simple addition of water and/or aggregates (Mehta & Monteiro, 2014). They may contain admixtures and other components when producing special concretes is required. In the production of conventional concrete, PC is generally used in smaller quantities than aggregates (≈15%); however, as shown in Figure 3, it represents up to 90% of the total CO_2 emissions.

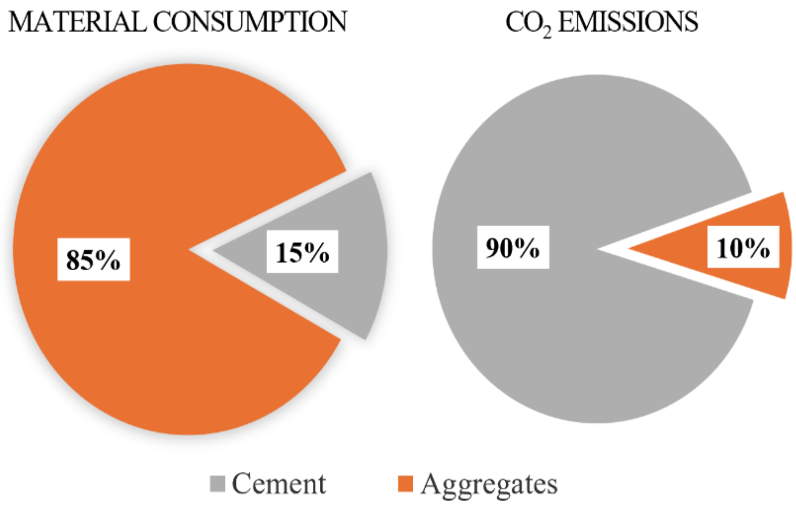

Figure 3. Consumption of aggregates and PC, and CO_2 emissions of cement and aggregates to produce 1 m³ of conventional concrete (fck 20 – 50 MPa), compiled from Goulart (2023).

It is understood that promoting decarbonization within the concrete supply chain is more complex than doing so within the cement industry. In Brazil, there are roughly one hundred cement plants across the territory, a number significantly lower than that of concrete batching plants, which are present in most Brazilian municipalities, with multiple units in larger cities. This disparity makes the process more complex. Since the largest share of CO_2 emissions in the supply chain of cement-based materials and services stems from Portland cement (Figure 4), decarbonization strategies for the concrete chain focus on process optimization, appropriate material proportions, and the use of new mix design methods and lower-emission aggregates. On the sectoral scale, the impression is that progress in this direction remains slow.

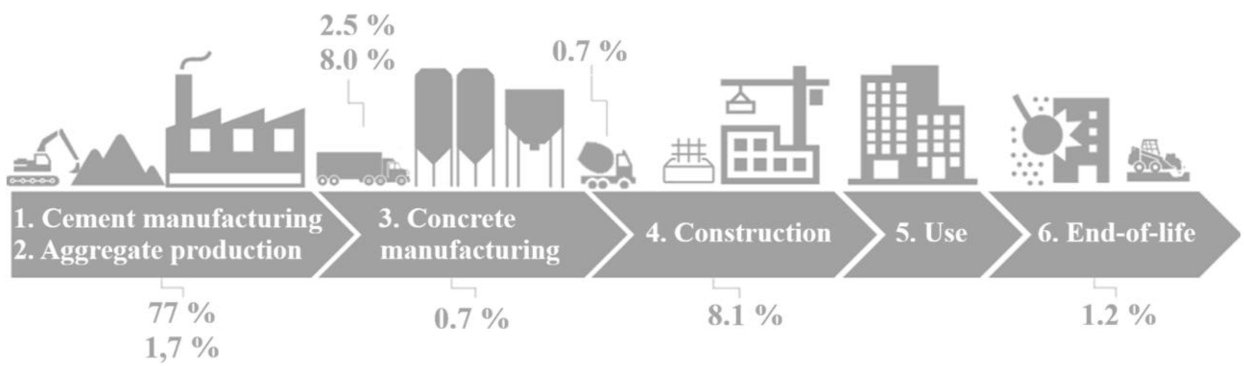

Figure 4. CO_2 emissions in the life cycle of cement and concrete (Climateworks, 2025).

On the other hand, the cement sector has, for years, implemented decarbonization strategies, especially those with highly competitive potential to reduce production costs, by reducing the clinker content in cement. In the primary national (ROADMAP BRASIL, 2019) and international (WBCSD, 2018) cement sector Roadmaps, key decarbonization strategies include reducing clinker content in cement through the substitution of clinker with lower-emission materials; greater energy efficiency in production processes; and fuel switching in kilns. The literature indicates that replacing clinker with SCMs could have reduced CO_{2eq} emissions by up to 1.3 gigatons in 2018 (Shah et al., 2022). Figure 5 illustrates the implementation of this strategy in Brazil. It can be observed that, since the end of the last century, the clinker content in PC has declined, directly reducing the material's CO_2 emissions. Currently, the clinker-to-cement ratio is approximately 0.62, with a forecast to reach 0.52 by 2050, which would allow to produce cements with less than

375 kg of CO_2 per ton (ROADMAP BRASIL, 2019). The literature mentions that increasing the fineness and/or increasing the C_3S and C_3A content of the cement are strategies that can be employed to enhance the reactivity of PC (Bentz; Sant; Weiss, 2008).

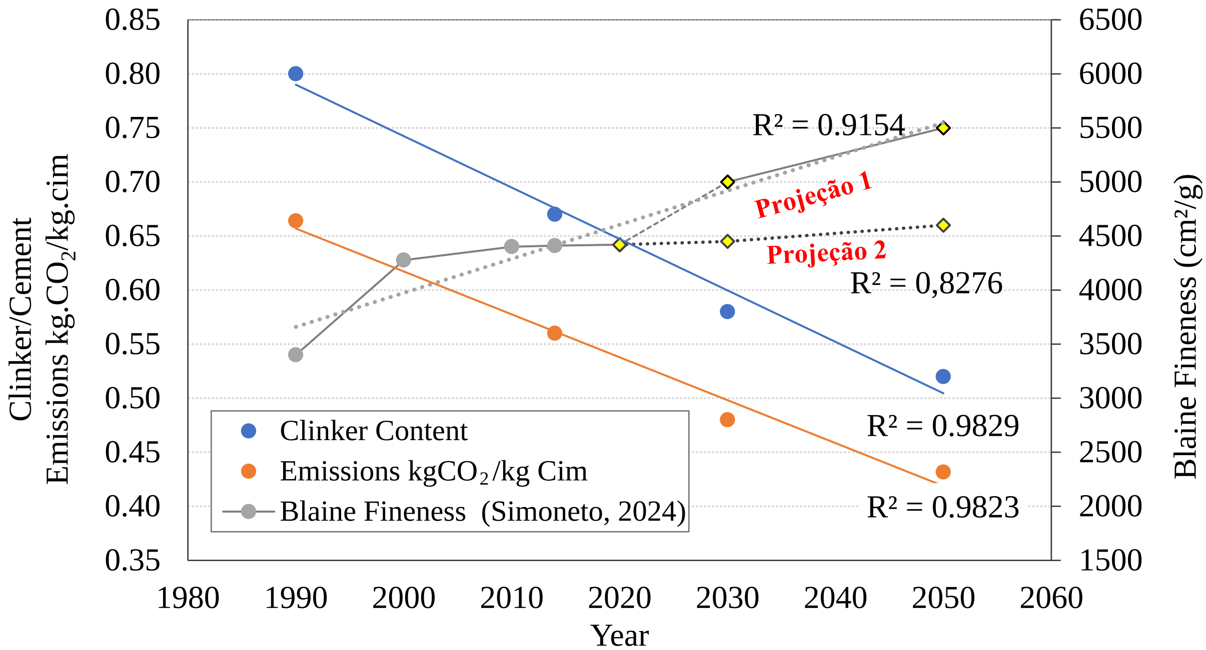

Figure 5. Reduction of clinker content in cement Roadmap Brazil (2019) and changes in Blaine fineness over the years (Simoneto, 2024).

To understand how this substitution process is possible while maintaining the 28-day compressive strength of the cement, Simoneto (2024) conducted a statistical study using secondary results from papers published over the last 30 years that employed different Brazilian PCs. The author found that, in parallel with the reduction in the clinker factor, the cement's Blaine fineness increases (Figure 5, gray line). In 1990, the fineness of Brazilian PC was approximately 3400 cm²/g, and the clinker content was 0.79. By 2020, the average fineness was around 4420 cm²/g, and the clinker content was 0.65. Based on data projections with an R^2 of 0.91, the average fineness of PC could reach nearly 5500 cm²/g in 2050, with a clinker content of 0.52. In fact, Simoneto (2024) found that some Brazilian cements already exhibit fineness levels close to the 2050 threshold, particularly CP V-ARI (High Early Strength Portland Cement) and CP II-F 40 (Portland-filler cement, 40 MPa class). These changes intensified after 2018, following the update of cement standards, which were replaced by NBR 16697 (ABNT, 2018), allowing higher replacement levels of clinker with fillers and SCMs.

The increased specific surface area of the cement particles results from finer clinker grinding, the use of high-fineness fillers or supplementary cementitious materials, or a combination of both. However, in Simoneto’s (2024) study, due to the methodology used to collect secondary data, it was not possible to identify the origin of this fineness. It has been known for years that cement with a high surface area requires higher water consumption and generates a greater amount of heat during the hydration process (Mehta & Monteiro, 2014), demanding special care in both production and the pouring of large volumes in massive elements, such as blocks, primarily to avoid problems associated with water demand and heat release.

In another study, Funahashi et al. (2024) compiled approximately 1,700 primary results (physicochemical analyses and heat of hydration tests using the Langavant bottle method up to 168 hours) for Brazilian CP II-E and CP III cements (ABNT, 2018) produced over the last two decades

(2004 to 2024) by five different manufacturers (A, B, C, D, and E). The authors also observed an increase in Blaine fineness over the years (Figure 6), corroborating Simoneto's (2024) findings. For CP II-E, the heat of hydration increases over time, whereas for CP III, despite the dispersion of results, it shows a downward trend.

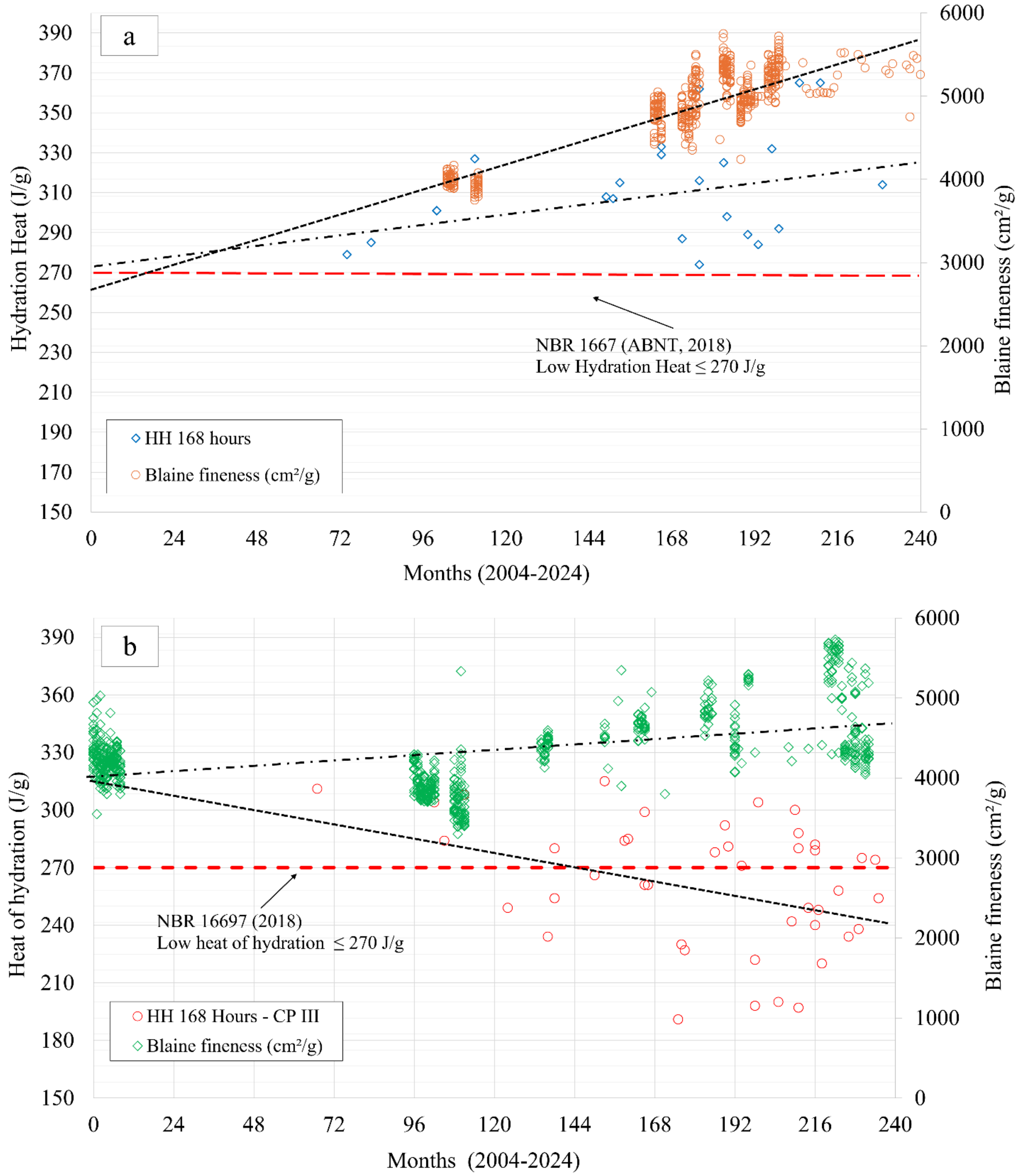

Figure 6. Blaine fineness and heat of hydration for cements a) CP II-E b) CP III, analyzed between 2004 e 2024 (Funahashi Jr et al., 2024).

For CP III cement, despite the increase in Blaine fineness, heat generation has decreased over recent years, which may be associated with the increased blast-furnace slag content used as an SCM (Funahashi Jr. et al., 2024). In addition to the increase in hydration heat, an increase in SO_3 content was noted, especially in Portland-slag cement (CP II-E). Based on average values from test data before the cement standard update in 2018, Funahashi et al (2024) verified an increase of 21% and 28% in SO_3 content for CP II-E and CP III cements, respectively. Furthermore, CP II-E cement showed reduced MgO and alkali levels, whereas CP III showed a trend toward higher MgO and Al_2O_3 levels. The results from Funahashi et al. (2024) and Simoneto (2024), developed using different research strategies and databases, indicate that Brazilian Portland cements have undergone significant physicochemical changes in recent years. It is the designer's responsibility to understand these changes and incorporate design solutions and concrete specifications to minimize their effects. One such effect is DEF (Delayed Ettringite Formation); to prevent its occurrence, the literature recommends not exceeding temperatures of 60°C and/or 65°C (Haspryk et al., 2023). Beyond fineness, the chemical composition of the cement plays a vital role in the development of expansive reactions. Cements with higher tricalcium aluminate (C_3A) content associated with higher SO_3 pose greater risks of sulfate attack and the development of DEF (Funahashi Jr et al., 2024; Haspryk et al., 2023). Based on chemical composition as a durability measure, the authors highlight that the SO_3/Al_2O_3 and $(SO_3)_2/Al_2O_3$ ratios should be lower than 0.50 and 2.0, respectively.

In addition to these issues, reducing clinker content lowers the cement's alkaline reserve, allowing faster CO_2 diffusion into the concrete. This can be detrimental to reinforced concrete elements subject to CO_2 action and moisture, due to the risk of corrosion caused by the depassivation of the reinforcement through the carbonation process (Possan, 2010; Possan et al., 2018). Alexander & Beushausen (2019) report an increased interest in the literature regarding carbonation modeling, particularly related to the growing use of supplementary cementitious materials (SCMs). They emphasize that developed models must consider the chemistry (carbonatable material) and the reactivity of the SCM, accounting for the relationship between physical and chemical resistance to CO_2 penetration; the same applies to chlorides (Alexander & Beushausen, 2019).

Regarding the variation in SCM content, Simoneto (2024) conducted an *in situ* study to evaluate aspects of on-site conventional concretes produced with cements of different clinker levels. The concretes were produced by workers in five batches per cement type without researcher's interference. The results found (Table 1) indicate that the cement with higher clinker content (CP V-ARI) showed better eco-efficiency and durability indicators than the lower-carbon cement (CP II-Z). To estimate the DSL (Design Service Life, corresponding to the corrosion initiation period) for simulating chloride and CO_2 diffusion (carbonation), the models by Andrade et al. (2017) and Possan et al., 2018 were employed, respectively, considering fair-faced concrete (uncoated). In the simulations, the exposure environment was outdoor, sheltered from rain, with a CO_2 concentration of 422 ppm, a relative humidity of 73%, and a temperature of 25°C. The DSL Index (I_{DSL}), in kg.cement/year, was calculated as the cement consumption required to produce 1 m³ of concrete divided by the simulated DSL based on the 28-day compressive strength (Equation 1). The lower this indicator, the better.

$$I_{DLB} = \frac{kg.cement/m^3}{DLB} \quad (1)$$

The Binder Intensity (BI) and Carbon Intensity (CI) indices were calculated according to the literature (Damineli et al., 2010; Oliveira et al., 2023), also considering that “lower is better”.

As shown in Table 1, under the production conditions of these on-site concretes, produced without technical guidance or control of materials and processes, the technical, environmental, and sustainability indicators were less favorable for the lower-carbon cement. This indicates that for the decarbonization process to be truly effective, it is necessary to work across the entire material supply chain to prevent performance loss during application. Otherwise, carbon may simply be shifted from one place to another: from the cement to the concrete. In this sense, Adesina e Zhang (2024) emphasize that merely reducing the embodied carbon of constituent materials is insufficient to ensure the practical sustainability of concrete; the implications of using low-carbon materials as substitutes for conventional constituents in the mix must also be analyzed. The authors state that it is necessary to use materials with lower environmental impact while also producing more durable concrete to ensure long-term performance (Adesina & Zhang, 2024). In the analyzed case (Table 1), the BI, CI, and IDSL indices were slightly lower, which is desirable, for concretes produced with CP V-ARI cement, which has a larger carbon footprint per ton compared to CP II-Z cement (Possan, 2019). This is because, in practice, concretes produced with CP V-ARI showed compressive strength 22% higher, directly impacting the environmental and durability indicators under evaluation.

Table 1. Technical-environmental and durability indicators of conventional on-site concrete produced with different types of cement, extracted from the study by Simoneto (2024).

Indicators		**Portland Cement (ABNT, 2018)**	
		CP V ARI	**CP II Z 32**
Fc (MPa)		25.0	19.3
Cement consumption (kg/m³)		305.0	298.0
BI (kg/kg.Cement/MPa)		12.4	13.4
CI (kg.CO_2/MPa)		11.1	12.5
CO_2 diffusion (Possan, et al., 2018)	Xc (mm)	17.7	30.0
	DSL (years)*	99.5	32.2
	I_{DSL} (kg.Cement/ano)	3.1	9.9
Cl diffusion (Andrade et al., 2017)	Cl (mm)	60.58	71.31
	DSL (years)**	21.5	15.5
	I_{DSL} (kg.Cement/ano)	14.2	19.2

Concrete cover adopted in simulations: * 25 mm ** 40 mm. Fc = compressive strength of concrete at 28 days. BI = binder intensity. CI = carbon intensity. Xc = carbonation depth for a 50-year service life (DSL). Cl = chloride penetration for a 50-year service life (DSL). DSL = design service life. I_{DSL} = design service life index.

Compressive strength is a critical indicator of concrete's ability to withstand environmental damage (Félix et al., 2023). As this property is linked to porosity – lower strength corresponds to higher porosity – the ingress of aggressive agents becomes easier and the service life (DSL) shorter, which is undesirable from the perspective of construction durability and sustainability.

It is well known that the durability of cement-based materials is not an intrinsic property but depends on the interaction with the exposure environment (Scrivener, et al, 2018). Durability design involves selecting an appropriate combination of materials and structural detailing to ensure the structure's serviceability (Alexander & Beushausen, 2019). Durability studies are necessary for analyzing the service life of concrete structures, which is holistic in nature (Castro-Borges & Helene, 2013; de Brito & Kurda, 2021) and must be evaluated through time stages in which specific phenomena occur (Castro-Borges & Helene, 2013). However, durability studies involve significant costs and require long analysis periods, which hinders development (Pauletti, 2004). In short, durability design requires an intrinsically holistic approach capable of integrating physicochemical

changes in PC, time-dependent phenomena, and performance requirements throughout the service life; otherwise, low-carbon solutions may yield apparent benefits but result in less durable structures and higher rehabilitation demands in the future.
In summary, the demand to reduce CO_2 emissions associated with cement production – achieved mainly by reducing clinker content – is affecting the material's physicochemical characteristics. This creates new challenges, especially regarding compliance with construction durability criteria. Given the speed of these occurrences, durability studies have been unable to keep pace with the changes. Furthermore, as the durability of Ordinary Portland Cement (OPC) materials has been studied for over a century, research in this field is often not considered innovative and is rarely accepted for publication. This discourages further research, leaving gaps in the understanding of how cement decarbonization affects concrete durability.

4. FROM STRENGTH TO DECARBONIZATION

Since the advent of Portland cement, approximately 200 years have passed, a period that, as shown in Figures 1 and 2, coincides with significant developments in humanity and GHG emissions. Along this path, many changes have occurred, as illustrated in the outline presented in Figure 7, which has been updated from Possan (2010) to include current issues. In this representation, it is observed that in the early stages of the development and dissemination of reinforced concrete, elements and structures were conceived and designed based on common sense and professional experience. The primary characteristic controlled was compressive strength, which was long considered a reliable parameter for project specifications. At that time, compressive strength values ranged from 10 to 20 MPa, with structures and elements exhibiting high robustness. It was believed that concrete, produced from the Portland cement newly discovered by Joseph Aspdin in 1824, behaved like rock, with durability extending far beyond the human life cycle.

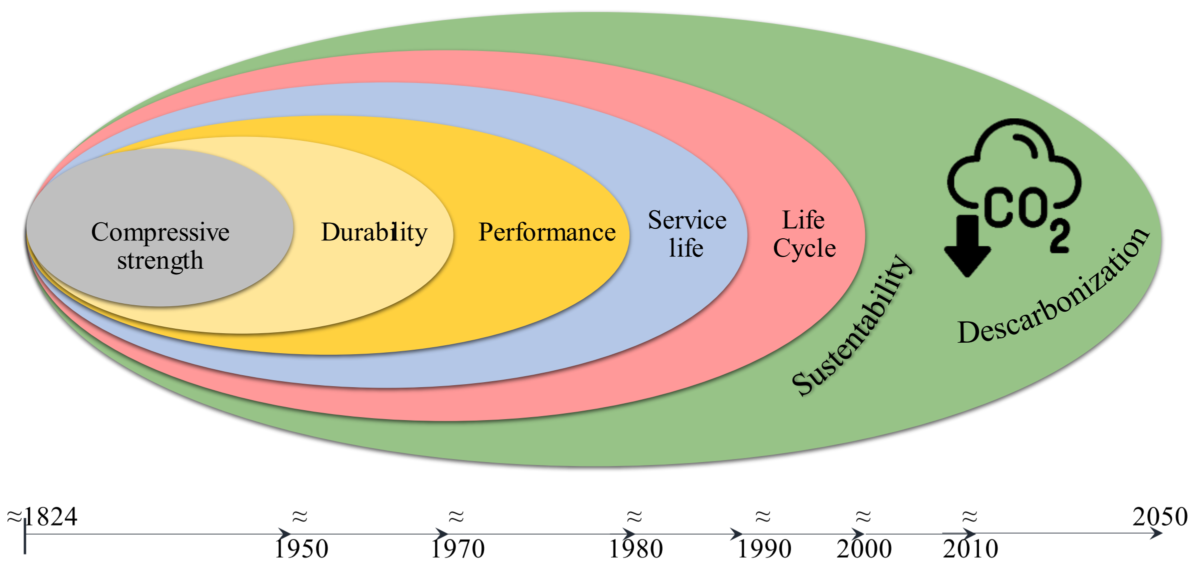

Figure 7. Conceptual evolution of concrete over time (updated from the figure proposed in the doctoral thesis of Possan, 2010; Possan et al., 2018).

However, over time, and with the recording of the first occurrences of unexpected material behavior, durability studies began to consider the exposure environment and in-service behavior, leading to the emergence of the concept of performance. Around the 1950s, durability was understood as the interaction between the material and the exposure environment, as it was found

that external aggressive agents, such as chloride ions and carbon dioxide (CO_2), can degrade PC-based materials. In parallel, it became necessary to indicate the "time" during which the concrete would meet design requirements, considering its use (performance) and environmental actions (durability); this led, at the end of the last century, to studies on deterministic and probabilistic service life. Furthermore, at the turn of the 21st century, factors such as competitiveness and environmental preservation drove changes in how structures should be conceived, requiring them to be designed holistically, considering the building life cycle.
Initially, life cycle assessment focused on "cradle-to-grave" aspects. Still, with the advancement of the circular economy (CE), this perspective shifted to "cradle-to-cradle," seeking the continuous reuse of resources and materials. Within this trend, the concept of sustainability for concrete structures began to be debated by various researchers and organizations worldwide, leading to the first guiding documents, mostly theoretical, on the subject, notably fib 53 (2010) e fib 2020 (2024). Only in the last 10 years has the concept of decarbonization gained traction in the sector, especially in the cement industry, emerging as a measurable indicator of achieving sustainability. To decarbonize is to reduce the carbon and energy footprints of products and processes. New technologies can drive this slow, gradual process and are paramount to containing ongoing global warming.
Generally, the current understanding is that sustainable concrete is durable concrete (fib, 2024; Martinez et al., 2025; Possan et al., 2018). Recent studies (Gursel et al., 2023; Martinez et al., 2025) demonstrate that longer-lasting structures either through the durability of the materials used (Martinez et al., 2025) or via mechanisms for reusing existing structures in the built environment for new applications (Gursel et al., 2023) are more sustainable; that is, they have lower global warming potential. More durable concrete can significantly reduce CO_2 emissions associated with cement. Roman concrete, given its long-lasting durability, offers interesting insights for modern concrete with a view toward low-carbon construction, such as the use of biomass as a fuel source (Martinez et al., 2025). While reducing carbon emissions, emerging technologies such as CO_2 mineralization (Proença et al., 2024), bio-based materials, and 3D printing promise to revolutionize construction methods (Kumar et al., 2025). Innovations in materials (Proença et al., 2024), improved proportioning methods for cement-based materials (Oliveira et al., 2025), the use of digital technologies such as artificial intelligence (AI) (Felix et al., 2021) and the Internet of Things (Barbhuiya et al., 2025), as well as carbon capture and utilization technologies (Aceituno et al., 2025; Emanuelsson et al., 2025; Yan & Zhang, 2019) are essential for the production of low-carbon concrete (Barbhuiya et al., 2025). Biomimetric-based solutions, such as the use of biological agentes for crack recovey in concrete structures (De Rooij et al., 2013; Ghellere et al., 2025; Jonkers & Schlangen, 2007; S. Kumar et al., 2025; Lenz et al., 2023), show potential to produce resilient and durable structures.

5. FUTURE PERSPECTIVES

The decarbonization of the cement industry represents an inevitable and strategic transition to meet global net-zero targets by 2050. However, this process requires the sector to move from a logic centered on direct emission reduction toward an integrated approach that also considers impacts on the performance and durability of concrete structures.
Among the main trends observed, the substitution of clinker with supplementary cementitious materials (SCMs), such as slag, fly ash, limestone filler, and calcined clays stands out. While these substitutions contribute to emission mitigation, they impose technical challenges related to maintaining reactivity and ensuring the service life of structures, demanding rigorous control of mix design, curing, and compatibility between constituents.
Another consolidated trend is the increase in cement fineness and reactivity, a strategy aimed at

compensating for the reduced clinker content. However, this may increase hydration heat and favor the development of pathological manifestations, such as delayed ettringite formation (DEF) and thermal cracking at early ages.
On the technological horizon, the advancement of Carbon Capture, Utilization, and Storage (CCUS) solutions is projected, which are fundamental for achieving net-zero emissions from 2030 onward. In Brazil, recent policies such as Law No. 15,042/2024 signal the country's entry into this emerging market, which is still undergoing international consolidation.
Recent perspectives also point to the integration of decarbonization and durability as a strategic axis. The literature emphasizes that, without considering long-term performance, the sector risks shifting the problem from cement to concrete, leading to indirect emissions from frequent maintenance or premature reconstruction. Thus, it is imperative to incorporate durability criteria into carbon mitigation plans to ensure the practical environmental benefit of low-carbon solutions.
Additionally, we observe the advancement of emerging technologies, including CO_2 mineralization, bio-based materials, cement with self-healing agents, and 3D concrete printing, which promise to redefine construction practices and sustainability paradigms. In parallel, the adoption of circular economy principles and the extension of the service life of existing structures constitute fundamental pillars of the transition toward a more resilient, lower-impact built environment.
Since Portland cement is the primary raw material in the cement-based materials chain, its physicochemical characteristics affect all stakeholders; it is necessary to think holistically, considering the production processes of cement and concrete together. Because durability studies are complex and require long analysis periods, a gap exists in the literature regarding the durability behavior of concretes produced with decarbonized cement.
Notably, over the last few decades, consumer goods have changed in response to technical and economic adjustments, and, recently, environmental changes have become necessary. This is the case with Portland cement: in physicochemical terms, the Portland cement produced in 2025 is slightly different from that made at the beginning of the 21st century and in the previous century. The fact that the material is different is not a problem. The central question is how to use it to maintain concrete performance over time.
In summary, it is necessary to do more with less and move from "the best cement and concrete in the world to the best cement and concrete for the world." The remarkable durability of Roman concrete can serve as an inspiration for this.

6. CONCLUSIONS

The decarbonization of Portland cement is a necessary pathway to meet global climate mitigation targets, yet its implications for the durability of concrete structures cannot be overlooked. The physicochemical alterations resulting from reduced clinker content and the expanded use of SCMs modify cement behavior and impose new performance challenges throughout its service life. In this context, sustainability depends on a holistic approach that integrates production, composition, mechanical behavior, and durability, avoiding low-carbon solutions that compromise in-service performance. Advancing this balance requires continuous research, more robust evaluation methods, and designs that reconcile environmental responsibility with structural longevity.

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