Technological, Socio-Environmental, and Educational Perspectives in Civil Construction



EDITORS

Cláudia Terezinha Kniess · Guilherme Leite Gaudereto · Ramoel Serafini
Renan Pícolo Salvador · Rodrigo Teixeira Bento

sãojudas

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Editors

Cláudia Terezinha Kniess · Guilherme Leite Gaudereto · Ramoel Serafini
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Preface

If we could travel back in time some 100 years and ask people going about their daily lives about the social and technological achievements the future might hold, we would get a picture that could contrast sharply with present-day reality. If, for example, we asked whether it would be possible to reduce social prejudice and guarantee women conditions equivalent to those of men in similar roles, they might answer that, with a little effort and greater social awareness, this would be entirely achievable. On the other hand, if we asked these ancestors of ours about the possibility of a machine formulating logic-based solutions on its own, they would say it was impossible, the stuff of science fiction.

Well, today we must deal with the impossible already achieved while still investing a great deal of energy and work to eliminate problems that should have been eradicated long ago. In this scenario of sharp contrasts and challenges that force us out of our comfort zone, we cannot forget that the main focus must be people. Technology is an extremely important tool for improving the quality of life of our society, but without care for education and for the training of people, this is not sustainable. Higher education and graduate education must be treated with the utmost attention, because the educators of our society depend on them, a society that still greatly lacks quality public primary and secondary education, which makes this challenge particularly complex. It is not possible to conceive of an egalitarian society without due investment in education.

Likewise, the development of robust infrastructure is a proven, effective strategy for reducing social inequality, especially when we consider urban areas, where most of the population is now concentrated. In the case of Brazil, we face the challenge of being the seventh most populous country in the world, with almost 90% of that population living in urban areas and demanding an immense amount of resources in terms of water, energy, and transportation. These demands must be met with minimal environmental impact so that future generations are not penalized by today's decisions. Otherwise, our descendants may come to think very negatively of the positions taken today.

Thus, with due commitment, we cannot downplay the size of the problems to be faced, and, consequently, all efforts to mitigate them are very welcome. For this reason, I am very pleased with the outcome of this publication, which, although quite diverse, focuses on a series of relevant problems, such as education and the sustainable production of infrastructure, especially urban infrastructure, in which the use of waste is essential to ensuring the sustainability of these actions. All of these actions contribute to reducing social inequality, as, evidently, does addressing the problem of how women are treated in the construction industry, and they are fundamental to increasing justice in our society. In this sense, all technologies and tools must be evaluated with due attention, given that the problem is multifaceted and broad. I must therefore state that this publication deserves high praise because it certainly brings contributions to Brazilian society in many highly relevant respects. May you, reader, enjoy the body of work published here, as well as, in particular, the topics closest to your interests. Enjoy your reading!

Prof. Dr. Antonio Domingues de Figueiredo
Polytechnic School of the University of São Paulo

Introduction

It is with great pleasure that I present the book *Technological, Socio-Environmental, and Educational Perspectives in Civil Construction*, produced under the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu. The book stems from a conviction that guides the work of our program: the construction industry cannot be approached from a purely technical standpoint. It is at once a driver of economic development, a source of environmental impact, and an agent of social transformation. Accordingly, the eleven chapters gathered here are organized into three complementary parts. The first situates the built environment within the 2030 Agenda, with discussions on energy poverty, urban regeneration, social housing, and applications of artificial intelligence in engineering. The second addresses materials, waste, and performance, with emphasis on fiber-reinforced concrete, the carbon footprint of sprayed concrete, and the valorization of industrial and natural waste as raw material. The third focuses on people, equity, and education, examining the presence of women in the sector, the training of engineers for sustainability, and the alignment of Brazilian graduate programs with the Sustainable Development Goals.

This work is the result of the collective effort of faculty members, researchers, alumni, and master's students, in dialogue with collaborators from institutions in Brazil and abroad. This dialogue lends the volume a diversity of perspectives that I regard as one of its greatest strengths. We have sought to combine scientific rigor with practical applicability, consistent with the professional nature of our master's program, offering contributions of value to academia as well as to practitioners, public managers, and companies in the sector. I thank the authors for their dedication and Prof. Dr. Antonio Domingues de Figueiredo, of the Polytechnic School of the University of São Paulo (Escola Politécnica da USP), for his generous preface. I hope this book will inspire new research and practices capable of making the construction industry more innovative, sustainable, and equitable.

Prof. Dr. Rodrigo Teixeira Bento
Editor-in-Chief and Professor, Professional Master's Program in Civil Engineering, USJT

PART I

The 2030 Agenda and the built environment

CHAPTER 1

Energy poverty and sustainable development: the 2030 Agenda and the Brazilian context

Guilherme Leite Gaudereto, Paulo Cesar de Abreu Paiva Junior, Michele Cavalcanti Toledo, Doris Jimena Roncancio Benítez, Francinaldo Alves da Silva, Felipe Augusto Matiello Bissoli

1. INTRODUCTION

The relationship between energy and human development is among the central issues of the contemporary agenda for planning, infrastructure, and public policy (McCollum et al., 2018; IEA, 2025). The provision of reliable, modern, and affordable energy services depends on the integration of physical infrastructure, energy generation and distribution systems, formal sectoral planning instruments, end-use technologies, and cross-sectoral coordination, encompassing technical, economic, social, and environmental dimensions (Mercure et al., 2019). Within this framework, the energy sector intersects, to varying degrees, with all the Sustainable Development Goals (SDGs) of the 2030 Agenda, while also being directly linked to key engineering issues such as energy efficiency, building performance, environmental quality, urban planning, and the resilience of infrastructure systems (UN, 2015; Fuso Nerini et al., 2018).

Energy poverty has emerged as a significant manifestation of the structural inequalities that constrain effective access to these services, affecting not only the fulfillment of basic daily needs, such as cooking, lighting, and thermal regulation, but also opportunities for productive engagement, education, healthcare, and social participation (Bouzarovski; Herrero, 2017; Gomes, 2018). Contemporary discussions on the subject gained prominence following the publication of Brenda Boardman's (1991) seminal work. Since then, the concept has evolved to incorporate additional analytical dimensions, including energy affordability, physical access to modern energy sources, service quality and reliability, the adequacy of end-use technologies, the safety of household energy installations, ventilation, thermal comfort, and the energy performance of buildings (Bouzarovski, 2014).

The heterogeneity of the phenomenon, combined with the absence of a universally accepted definition, has prompted methodological efforts aimed at its measurement and at the design of policies tailored to specific socioeconomic and territorial contexts (Ochoa, 2014; Gomes, 2018). In Brazil, energy poverty has distinctive characteristics, shaped by the coexistence of a predominantly renewable electricity mix, high rates of electricity access, and the persistence of less visible forms of energy deprivation. These include the continued use of traditional fuels for household energy needs, particularly firewood for cooking, the combined use of biomass and liquefied petroleum gas (LPG) among vulnerable households, regional disparities, and the limitations of aggregated indicators in capturing dimensions such as energy affordability, service quality, thermal comfort, and the technological adequacy of housing. Estimates by Bezerra et al. (2022) show that these deprivations persist in the country, with higher incidence in rural areas. Together with sectoral challenges related to expanding energy supply, decarbonization, energy efficiency, the governance of the 2030 Agenda, and improvements to the built environment, these factors define an analytical field in which sustainable development, infrastructure, and the reduction of social inequalities are closely intertwined.

This chapter examines energy poverty from the perspective of sustainable development, integrating the international conceptual framework, the monitoring framework of the 2030 Agenda (with particular emphasis on SDG 7), and the specific manifestations of the phenomenon in Brazil. The discussion is analytical and literature-based, drawing on specialized academic publications, institutional reports, and recent indicators related to energy, sustainable development, and energy poverty. Particular attention is given to the intersections between energy planning, the built environment, energy efficiency, cooking technologies, and territorial inequalities.

The chapter comprises seven sections. After outlining the 2030 Agenda and SDG 7, it presents the conceptual foundations of energy poverty and its global and Latin American manifestations. It then examines Brazil, addressing prevalence; firewood and cooking; regional disparities; social, health, environmental, and technological implications; and the principal analytical and policy challenges.

2. ENERGY, SUSTAINABLE DEVELOPMENT, AND THE 2030 AGENDA

Global energy demand has increased substantially over recent decades, driven by population growth, economic expansion, industrialization, and rising per capita energy consumption, particularly in emerging and developing economies (Energy Institute, 2025). According to the Statistical Review of World Energy 2025 (Energy Institute, 2025), this

trend is reflected in total primary energy supply, which reached 592 EJ in 2024 following an annual growth rate of 2%, setting a new record. From a long-term perspective, this trajectory underscores the enduring centrality of energy to the functioning of contemporary societies, despite short-term fluctuations such as the decline observed in 2020 due to the COVID-19 pandemic and the subsequent instabilities associated with geopolitical shocks, supply constraints, and volatility in global energy markets.

According to the same report, the global energy mix continues to be dominated by fossil fuels. In 2024, oil, coal, and natural gas accounted for approximately 34%, 28%, and 25% of total primary energy supply, respectively, while nuclear energy represented about 5%, hydropower approximately 3%, and other renewable sources around 6%. Collectively, fossil fuels still accounted for approximately 87% of the global energy mix, indicating that although renewable energy sources have expanded significantly, they continue to coexist with a high level of dependence on nonrenewable fuels. The report itself characterizes this situation as an ongoing but disorderly energy transition, in which oil, natural gas, coal, and renewable energy sources have all reached historically high levels of use simultaneously.

Although renewable energy sources, particularly wind and solar, have grown at rates exceeding those of overall energy demand, their current share remains insufficient to fundamentally alter the short-term dominance of fossil fuels in the global energy mix. In this context, the transition toward a predominantly renewable energy system depends on substantial changes in investment flows, transmission and storage infrastructure, regulatory frameworks, and the capacity to coordinate energy policies, particularly in developing countries (McCollum et al., 2018; IEA, 2025). Furthermore, as highlighted by Mercure et al. (2019), strategic decisions in the energy sector tend to generate cascading effects across other dimensions of sustainable development, including water resource management, food production, the conservation of natural ecosystems, and climate change mitigation.

Recognition of this cross-cutting role reflects the evolution of the sustainable development concept, whose contemporary foundation is generally traced to the definition proposed by the Brundtland Commission in 1987, according to which sustainable development is understood as meeting the needs of the present generation without compromising the ability of future generations to meet their own needs (Tremblay et al., 2021). This conceptual framework was subsequently refined through international conferences such as the Rio Earth Summit (Rio-92) and Rio+20, culminating in the adoption of the 2030 Agenda for Sustainable Development by the United Nations in 2015 (UN, 2015).

The 2030 Agenda for Sustainable Development was adopted during the 2015 United Nations Sustainable Development Summit, convened with the participation of all 193

United Nations Member States, and resulted in the establishment of 17 SDGs and 169 associated targets (UNDP, 2016). These targets are classified into outcome targets, which define or quantify the desired results, and means of implementation targets, which address the human, financial, technological, and governance resources required to achieve those outcomes (IPEA, 2018). According to Kamau, Chasek, and O'Connor (2018), the development of the 2030 Agenda was characterized by a multilateral negotiation process aimed at building consensus among developed and developing countries, while also involving intergovernmental organizations, nongovernmental organizations, the private sector, and civil society groups.

Unlike its predecessor, the Millennium Development Goals (MDGs), the 2030 Agenda is guided by the principle of interdependence among its goals and targets (UN, 2021). This principle has inspired analytical efforts to clarify the synergies and trade-offs across the different dimensions of sustainable development. Waage et al. (2015) proposed a framework in which the 17 SDGs are organized into three concentric layers representing well-being, infrastructure, and the natural environment, thereby highlighting the interdependence of these dimensions. Similarly, Rockström and Sukhdev (2016) introduced the SDG wedding cake metaphor, which conceptualizes the goals related to the economy and society as being fundamentally dependent on those associated with the biosphere. These frameworks have remained influential in subsequent literature as reference models for the integrated analysis of the 2030 Agenda (Barbier; Burgess, 2017; Scharlemann et al., 2020).

The energy sector occupies a central position within this framework. Fuso Nerini et al. (2018) found that approximately 67% of the 169 SDG targets require effective actions related to the energy sector, whereas 85% exhibit either synergistic relationships or trade-offs with SDG 7. This pattern of interconnectedness indicates that countries' progress toward sustainable development depends, to a significant extent, on strategic decisions made in the energy sector, particularly those concerning the expansion of energy supply, the transition to renewable energy sources, improvements in energy system efficiency, and the universal provision of modern, reliable, and affordable energy services (McCollum et al., 2018). From this perspective, energy poverty should not be understood merely as a sector-specific manifestation of inadequate access to energy but rather as a multidimensional challenge situated at the intersection of social inequality, infrastructure, public health, the built environment, and sustainable development.

3. SDG 7 AND THE MONITORING OF THE GLOBAL ENERGY AGENDA

Sustainable Development Goal 7 (SDG 7) commonly summarized as "Affordable and Clean Energy," represents the most direct link between the 2030 Agenda and the energy

sector. Its five targets encompass universal access to affordable, reliable, and modern energy services; a substantial increase in the share of renewable energy in the global energy mix; a doubling of the global rate of improvement in energy efficiency; strengthened international cooperation in research and clean energy technologies; and the expansion of infrastructure and technological upgrading to deliver sustainable energy services in developing countries (UN, 2015; ONU, 2024).

The implementation of the 2030 Agenda is monitored through dedicated global mechanisms. The High-level Political Forum (HLPF) serves as the principal intergovernmental platform for reviewing and assessing progress, at which countries submit their Voluntary National Reviews (VNRs), reports that document national experiences, achievements, challenges, and lessons learned in implementing the Sustainable Development Goals (UN, 2021). In addition, the United Nations periodically publishes the Sustainable Development Goals Report, which provides an annual assessment of global progress, and the Global Sustainable Development Report, which synthesizes scientific evidence to support countries in formulating policies and strategies for sustainable development (UN, 2023). Complementing these official monitoring mechanisms, the Sustainable Development Solutions Network (SDSN) publishes annual reports assessing progress toward the SDGs at the global level, offering comparative indicators that are particularly valuable in contexts where official statistics are incomplete or outdated (Sachs et al., 2023).

At the level of Brazil's formal energy planning instruments, the integration of the 2030 Agenda is reflected in the National Energy Plan (Plano Nacional de Energia – PNE), which establishes a long-term strategic outlook, and in the Ten-Year Energy Expansion Plan (Plano Decenal de Expansão de Energia – PDE), a medium-term planning instrument. Both are prepared by the Energy Research Office (Empresa de Pesquisa Energética – EPE) under the coordination of the Ministry of Mines and Energy (Ministério de Minas e Energia – MME) (MME; EPE, 2020, 2022). These instruments define guidelines for expanding energy supply, monitoring the national energy mix, and coordinating decision-making across sectors related to energy. Complementing these planning tools, mechanisms such as Strategic Environmental Assessment and Integrated Environmental Assessment, the latter applied in river basins with multiple hydropower developments, incorporate socioeconomic and environmental considerations into the decision-making process at different levels (Ruffato-Ferreira et al., 2017). Gaudereto's (2023) analysis of the incorporation of the SDGs into the PNE and successive PDEs indicates that the internalization of the 2030 Agenda remains uneven, with more consistent progress in infrastructure and economy-related issues than in social, environmental, and partnership dimensions.

Figure 1 summarizes global progress toward SDG 7, which remains insufficient for achieving the targets by 2030. Access to electricity and clean cooking, the share of

renewables in total final energy consumption, and energy efficiency have all improved; nevertheless, in 2023, about 666 million people lacked electricity and 2.1 billion lacked clean cooking solutions, especially in sub-Saharan Africa (IEA, 2025). Moreover, international financial flows for research, development, and production of renewable energy in developing countries remained below early-decade levels, revealing gaps in the international cooperation envisaged under SDG 7.

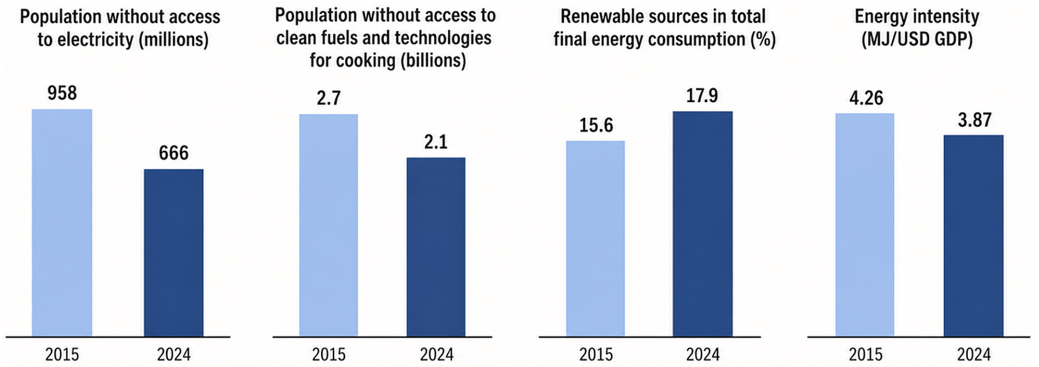


Figure 1 – Global SDG 7 indicators: status in 2010 and the most recent year available

Source: Adapted from UN, 2026.

Brazil submitted VNRs to the HLPF in 2017 and 2024, the latter amid renewed institutional commitment to the 2030 Agenda (Brasil, 2024). Indicators are monitored through the ODS Brasil platform, coordinated with the Brazilian Institute of Geography and Statistics (IBGE) and partner institutions. As of September 11, 2023, data had been produced for 121 of 254 indicators; 72 were under development, 51 lacked data, and 10 were not applicable (Brasil, 2023c). Table 1 presents the status of SDG 7 indicators in April 2026.

As of the reference date, SDG 7 had 83.3% of its indicators classified as produced. Of its five targets, data were available for four (Targets 7.1, 7.2, 7.3, and 7.b), whereas a data gap remained for Target 7.a, which addresses international financial flows to support renewable energy production in developing countries (Brasil, 2026). According to Indicator 7.1.1, electricity access among Brazilian households reached 99.8% in 2024, based on data from the Continuous National Household Sample Survey (Continuous PNAD/IBGE). Indicator 7.1.2, which measures the proportion of people living in households that use clean fuels for cooking, reached 95.4% in 2024, also based on the Continuous PNAD, thereby overcoming the data lag reported in previous assessments (Brasil, 2026).

The share of renewable energy in Brazil's total domestic energy supply (TDES), measured by Indicator 7.2.1, increased from 39.7% in 2014 to 47.4% in 2023. It reached a

peak of 48.7% in 2020, declined to 45.0% in 2021, and remained relatively stable in the following years. Energy intensity, measured by Indicator 7.3.1, remained relatively stable between 2015 and 2023, fluctuating between 0.078 and 0.081 metric tons of oil equivalent per thousand purchasing power parity (PPP)-adjusted U.S. dollars of GDP, using 2021 as the reference year. Finally, Indicator 7.b.1, which measures installed renewable electricity generation capacity per capita, increased from 525.36 W in 2014 to 891.39 W in 2023, according to data from EPE (Brasil, 2026).

Table 1 – Status of Brazil's SDG 7 indicators as of April 20, 2026

Target	Indicator	Status	Latest Update
7.1	7.1.1 — Population with access to electricity	Produced	2026
7.1	7.1.2 — Population with access to clean fuels and technologies	Produced	2026
7.2	7.2.1 — Share of renewable energy in the total domestic energy supply	Produced	2025
7.3	7.3.1 — Energy intensity (primary energy/GDP)	Produced	2025
7.a	7.a.1 — International financial flows to support renewable energy	No data	—
7.b	7.b.1 — Installed renewable energy generation capacity per capita	Produced	2025

Source: adapted from Brasil, 2026.

The international comparative assessment conducted by Sachs et al. (2023) classifies countries' performance on the SDGs into four categories: goal achieved, challenges remain, significant challenges remain, and major challenges remain. For Brazil, the report indicates a relatively favorable performance on SDG 7, a position that has remained consistent since the first country-specific assessment published in 2017 (Sachs et al., 2017). This assessment, however, should be interpreted with caution, as some of the indicators considered are based on data from 2015, the year in which the 2030 Agenda itself was adopted. In contrast, the Seventh Spotlight Report (VII Relatório Luz), prepared by the Civil Society Working Group for the 2030 Agenda (GTSC A2030, 2023), concludes that four of the five SDG 7 targets have experienced setbacks in Brazil, whereas the remaining target is considered to be in a vulnerable situation. From an analytical perspective, the two assessments measure different aspects of SDG implementation. The SDSN assessment relies on internationally comparable indicators and aggregated measures of access, often based on earlier baseline data, which tends to produce a more favorable evaluation. In contrast, the Spotlight Report adopts a civil society perspective and assesses

the recent trajectory of the targets, including dimensions such as energy affordability, service quality, and the weakening of governance structures—factors that are only partially captured by aggregated international indicators. Thus, the divergence reflects not so much factual inconsistency as differences in data sources, temporal scope, and the distinct purposes of each assessment framework.

The governance of the 2030 Agenda in Brazil has also experienced significant institutional discontinuities during the post-2015 period. The National Commission for the Sustainable Development Goals (CNODS), established in 2016 to coordinate the implementation of the Agenda among different levels of government and civil society organizations, was dissolved by Decree No. 9,759 of April 11, 2019. Adams et al. (2020) interpreted this measure as part of a broader process of weakening the governmental structures supporting the implementation of the SDGs. In 2023, however, the CNODS was re-established by Decree No. 11,704 of September 14, 2023, later amended by Decree No. 11,808 of November 28, 2023, signaling an effort to restore the institutional coordination of the 2030 Agenda in Brazil.

Data gaps, institutional discontinuities, and divergent assessments show that Brazil's favorable aggregate SDG 7 performance conceals important dimensions of energy poverty. Beyond formal electricity access, these include affordability, service quality and reliability, appropriate cooking technologies, thermal comfort, household safety, and territorial inequalities.

4. ENERGY POVERTY: ORIGINS, DEFINITIONS, AND ITS MULTIDIMENSIONAL NATURE

The concept of energy poverty became firmly established in academic research and public policy during the early 1990s, particularly following the publication of *Fuel Poverty: From Cold Homes to Affordable Warmth* by the British researcher Brenda Boardman (Boardman, 1991). Although the hardships associated with inadequate, insecure, or economically burdensome access to energy had long been recognized, especially among low-income households in regions with harsh winters, Boardman's work provided the first systematic treatment of the issue by linking the socioeconomic dimensions of energy access to measurable criteria. She proposed defining energy poverty as a condition in which households spend more than 10% of their income on domestic energy, a threshold that was initially adopted in the United Kingdom and subsequently influenced policy frameworks in other European jurisdictions (Boardman, 1991).

Since then, a range of conceptual approaches has contributed to refining the definition of energy poverty, highlighting its complementary dimensions. Bouzarovski (2014)

and Bouzarovski and Herrero (2017) characterize energy poverty as a condition of household energy deprivation or inadequacy, emphasizing its relationship with energy transitions, regional inequalities, and broader processes of social vulnerability. Gomes (2018), however, discusses the limitations of these approaches. Boardman's threshold-based definition does not directly address difficulties in accessing energy as an essential service, focusing instead on the proportion of household income allocated to energy expenditures. In turn, the relational definition proposed by Bradshaw and Hutton (1983) relies on socially determined reference standards, whose variability may complicate the design and calibration of public policies.

The conceptual diversity surrounding energy poverty reflects its inherently multidimensional nature. In developed countries, particularly those located in regions with harsh winters, the phenomenon is generally manifested as households' inability or difficulty in paying energy bills, resulting from the combined effects of high energy prices, low household incomes, and poor energy performance of buildings. In this context, inadequate housing conditions widen the gap between the amount of energy consumed and the level of thermal comfort actually achieved (Gomes, 2018). In developing countries, by contrast, energy poverty is more commonly associated with the absence or inadequacy of access to modern energy sources, unreliable energy supply, poor service quality, unsafe household energy installations, and the lack of appropriate appliances and technologies, particularly for cooking (Ochoa, 2014).

The consequences of energy poverty likewise encompass multiple analytical dimensions. In less developed regions, the lack of access to electricity reduces households' productive time, hinders food preservation, limits educational activities, and necessitates the use of inadequate lighting sources. At the same time, the combustion of firewood, charcoal, and other solid fuels in poorly ventilated environments increases exposure to household air pollution, with significant implications for residents' respiratory health (Gomes, 2018). Energy poverty also imposes broader social costs by limiting access to information, digital connectivity, education, and political participation, dimensions that are increasingly dependent on reliable electricity services. Furthermore, the literature documents important gender inequalities in the experience of energy poverty. In many settings, women and children bear a disproportionate share of fuel collection and the operation of traditional cookstoves, with adverse consequences for their health, school attendance, time use, and economic autonomy (Gioda, 2019).

The economic dimension of addressing global energy poverty was examined by González-Eguino (2015), who estimated that achieving universal access to modern energy sources would require annual investments of approximately US$35 billion over a period of two decades. This amount corresponds to roughly 0.08% of the combined GDP of

OECD countries, or about US$25 per capita per year. The author emphasizes that this investment is substantially lower than the level of subsidies allocated to fossil fuels, which totaled approximately US$540 billion in 2012. This comparison suggests that addressing energy poverty is not merely a matter of expanding energy infrastructure but also requires distributive policy choices, the reallocation of financial incentives, international cooperation, technology transfer, and capacity building in developing countries, in alignment with decarbonization commitments and the objectives of SDG 7 (Gomes, 2018).

Despite definitional diversity, energy poverty is now an important category for public policy because access to affordable, reliable, and modern energy services is a global priority. The absence of a universal definition has not prevented context-specific measurement; rather, it reinforces the need to calibrate metrics to socioeconomic, climatic, and housing conditions.

The literature has proposed composite indicators to overcome the limitations of exclusively threshold-based or relational definitions of energy poverty. Nussbaumer, Bazilian, and Modi (2012) developed the Multidimensional Energy Poverty Index (MEPI), which combines dimensions related to cooking, lighting, household appliances, entertainment, education, and communication. One of its main strengths is its ability to capture simultaneous deprivations across multiple dimensions of household life. In the United Kingdom, as part of a revision of the methodology originally associated with Boardman, Hills (2012) introduced the Low Income High Costs (LIHC) indicator, which classifies households as experiencing energy poverty when they simultaneously face energy costs above the national median and a residual income below the poverty threshold after accounting for those energy costs. Thomson, Bouzarovski, and Snell (2017) provide a comparative review of these and other indicators, demonstrating that methodological choices are not neutral, as different metrics prioritize different dimensions of the phenomenon.

5. ENERGY POVERTY FROM GLOBAL AND LATIN AMERICAN PERSPECTIVES

An analysis of energy poverty in Latin America, situated within the broader global context, requires the simultaneous consideration of two sets of factors. On the one hand, it involves the region's relative contribution to the global environmental impacts associated with the energy sector; on the other, it encompasses the structural inequalities that shape effective access to modern, safe, and affordable energy services. According to Ochoa (2014), in a report prepared for the Economic Commission for Latin America and the Caribbean (ECLAC), the region accounts for approximately 5% of global carbon

dioxide emissions from energy production and consumption, a share substantially lower than those of Asia and Oceania, North America, and Europe. This asymmetry highlights Latin America's relatively limited contribution to global emissions, even though the region continues to face significant socioeconomic and environmental challenges at the local, national, and regional levels.

Ochoa (2014) argues that, in the Latin American context, energy policies should place the social dimension of energy use at the center of decision-making, since low levels of per capita energy consumption, income inequality, and territorial disparities may prevent segments of the population from achieving minimum standards of well-being. This perspective remains highly relevant in light of recent monitoring of SDG 7, which shows that, despite global progress in expanding access to electricity and clean cooking, substantial regional, territorial, and socioeconomic inequalities persist. The regional challenge extends beyond the transition to lower-carbon energy systems. It also encompasses the effective universal provision of energy services, the reduction of inequalities in energy access, and the provision of adequate conditions for the safe and effective end use of energy.

In this context, energy poverty in Latin America differs from the patterns observed in cold-climate countries, where the debate has historically focused on households' ability to heat their homes and on the share of household income devoted to energy expenditures. In Latin America, the phenomenon is more commonly characterized by incomplete or inadequate access to electricity, unreliable or low-quality energy supply, relatively high energy costs for low-income households, the persistent use of solid fuels for cooking, inadequate housing conditions, and pronounced disparities among urban, peri-urban, rural, and remote communities.

The *Tracking SDG 7* report indicates that Latin America and the Caribbean have relatively high levels of access to clean fuels and technologies for cooking compared with other developing regions, although significant internal disparities remain. In 2023, access was estimated at approximately 91% in urban areas and 82% in rural areas (IEA, 2025). These figures suggest that the region should not be assessed solely in terms of the formal presence or absence of access but also with regard to territorial inequalities, the persistence of pockets of vulnerability, and the actual quality of energy services and conditions of energy use.

The magnitude of the challenge can also be understood from a historical perspective. Prior to the adoption of the 2030 Agenda, Modi et al. (2005, as cited in Ochoa, 2014) had already reported that billions of people relied on firewood, charcoal, or other traditional fuels for cooking, while a substantial share of the global population lacked access to electricity. More recent data indicate significant progress: in 2023, 74% of the world's population had access to clean fuels and technologies for cooking, compared with 64%

in 2015. Nevertheless, approximately one-quarter of the global population continued to rely on polluting fuels and technologies, and current projections indicate that, if existing trends persist, approximately 1.8 billion people may still lack access to clean cooking by 2030 (IEA, 2025). The report further emphasizes that, in rural and peri-urban areas of low- and middle-income countries, solid biomass, including firewood, animal dung, and agricultural residues, continues to be a common source of cooking fuel (IEA, 2025).

This context frames energy poverty as a problem of access, affordability, service quality and reliability, conditions of use, and territorial inequality.

6. THE MANIFESTATION OF ENERGY POVERTY IN BRAZIL

Assessing energy poverty in Brazil requires integrating the national energy mix, access across socioeconomic groups, and regional differences in end-use conditions. Brazil combines near-universal electricity access, a high renewable share in TDES, and relatively favorable SDG 7 indicators. Modern renewables represented 45% of total final energy consumption in 2022, one of the highest shares in the world (IEA, 2025).

Nevertheless, energy poverty persists among vulnerable populations, rural and peri-urban communities, and households using traditional cooking fuels (Gioda, 2019; Bezerra et al., 2022). Its analysis must therefore combine official statistics, national databases, and empirical studies on internal inequalities, firewood and biomass use, LPG dependence, affordability, and household end-use conditions.

6.1. Dimensions and estimates

Bezerra et al. (2022) define energy poverty in Brazil as the inability of certain households to secure adequate levels of energy services, encompassing activities such as cooking, lighting, heating, and the use of household appliances. Applying their methodology, the authors estimate that approximately 11% of Brazilian households experience some form of energy poverty, a proportion that rises to 16% when only rural areas are considered. These estimates provide an important starting point for understanding the specific manifestations of energy poverty in Brazil and demonstrate that near-universal access to electricity, although a significant achievement, does not by itself eliminate the broader challenges associated with the phenomenon.

Official statistics reinforce this interpretation. Indicators 7.1.1 and 7.1.2, discussed in Section 3, indicate strong performance in aggregate access, but they do not rule out specific forms of energy deprivation, particularly when territorial inequalities, service quality, energy affordability, and the continued use of firewood and charcoal in vulnerable

settings are taken into account. The near-universal coverage reflected in these aggregate indicators may also mask the precarious nature of access experienced by part of the population. In favelas and informal settlements, a proportion of electricity connections are informal or illegal, commonly known in Brazil as *gatos* (electricity theft through unauthorized connections). These improvised installations can overload distribution networks and increase the risk of short circuits and household fires (Mimmi; Ecer, 2010). At the system level, nontechnical electricity losses, partly associated with such irregular connections, accounted for approximately 6.6% of all electricity injected into the Brazilian grid in 2024 (ANEEL, 2025). Thus, access to electricity does not necessarily translate into a stable and safe energy service, a dimension that remains largely invisible in conventional coverage indicators.

The Brazilian context also reflects the trajectory of public policies aimed at expanding both access to energy and its affordability. The Light for All Program (Programa Luz para Todos), launched in 2003 and maintained through successive phases to the present day, played a key role in achieving near-universal rural and household electrification in Brazil. According to independent evaluations, the program benefited more than 15 million people during its period of greatest expansion (Slough; Urpelainen; Yang, 2015). Complementing these efforts, policies designed to improve energy affordability include the Social Electricity Tariff (Tarifa Social de Energia Elétrica), established by Law No. 12,212 of January 20, 2010 (Brasil, 2010), and the Brazilian Gas Assistance Program (Auxílio Gás dos Brasileiros), established by Law No. 14,237 of November 19, 2021 (Brasil, 2021). Both programs are targeted at households registered in the Single Registry for Social Programs (Cadastro Único para Programas Sociais).

The affordability of LPG is a key determinant of this scenario. The increase in LPG cylinder prices over the past decade has raised the share of income that low-income households must devote to cooking fuel and has been associated with the continued, or renewed, use of firewood as a household cost-saving strategy, particularly among low-income families and in rural areas (Coelho et al., 2018; Bezerra et al., 2022). Because responsibility for cooking and firewood collection falls predominantly on women, the regressive impact of rising LPG costs tends to exacerbate gender inequalities within households (Gioda, 2019).

The energy mix of the Brazilian residential sector remains concentrated in three main energy sources: electricity, firewood, and LPG, whereas natural gas, solar thermal energy, and other sources still account for relatively small shares. According to the 2025 National Energy Balance, total residential energy consumption reached 31.0 million metric tons of oil equivalent (Mtoe) in 2024, up from 30.1 Mtoe in 2023, representing an increase of 3.0%. Electricity remained the sector's primary energy source, with its share rising from 48.4% to 50.8% of residential energy consumption between 2023 and 2024.

Although still significant, the share of firewood declined from 25.0% to 22.9%, whereas LPG decreased slightly from 21.1% to 20.7%. Natural gas maintained a 1.5% share, solar thermal energy increased marginally from 2.8% to 2.9%, and other energy sources accounted for 1.2% of residential energy consumption in 2024 (EPE, 2025).

A disaggregated analysis by income group, however, shows that the aggregate residential energy mix may conceal important inequalities. The fact sheet *Residential Energy Consumption by Income Groups in Brazil*, published by EPE (2024), indicates that electricity consumption is heavily concentrated among higher-income households, whereas biomass, particularly firewood and charcoal, is used disproportionately by lower-income households. The report also highlights that cooking accounts for 52% of the residential sector's total energy demand and is supplied primarily by firewood and LPG. Consequently, lower-income households tend to exhibit greater unmet demand for energy services provided by modern energy sources, such as electricity, LPG, natural gas, and solar thermal energy, as well as greater potential for energy efficiency gains through the replacement of the remaining use of firewood and charcoal (EPE, 2024).

6.2. Firewood, cooking, and regional disparities

According to the methodology adopted by IBGE (2024), firewood is classified into two main categories: silvicultural firewood, derived from planted forest stands established and managed by human intervention until harvest, and extractive firewood, obtained through the harvesting of forest products from naturally occurring vegetation. In 2022, silviculture in Brazil produced approximately 7 million metric tons of charcoal, 52.7 million cubic meters of firewood, and 158.2 million cubic meters of roundwood; extractive activities, in turn, accounted for about 19.7 million cubic meters of firewood across the national territory (IBGE, 2024).

The regional distribution of this production is heterogeneous. In most of Brazil's major geographic regions, silviculture prevails over extractive production, although with marked differences: the South accounts for approximately 63.37% of the national volume of silvicultural firewood, with the states of Paraná and Rio Grande do Sul standing out, whereas the Northeast accounts for approximately 60.13% of the national volume of extractive firewood (IBGE, 2024). Of this national volume of extractive firewood, Ceará and Piauí account for 16.22% and 10.98%, respectively, whereas Rio de Janeiro and São Paulo exhibit only residual levels of firewood extraction compared with the other states. This regional pattern reflects not only differences in edaphoclimatic conditions and the availability of natural vegetation but also historical trajectories of territorial occupation and regional socioeconomic development (Travassos; Souza, 2014).

Figure 2 presents 2024 data on the regional distribution of charcoal and firewood production from silviculture, whereas the two preceding paragraphs refer to 2022. The data cover only production from planted forests, which is predominantly commercial and industrial in nature, rather than the extractive production and household consumption discussed in this section. Within this universe, the South Region concentrates 60.6% of firewood output and the Southeast Region 84.6% of charcoal output, whereas the Northeast, where extractive activities account for most firewood production, has a limited share of silvicultural output (IBGE, 2026).

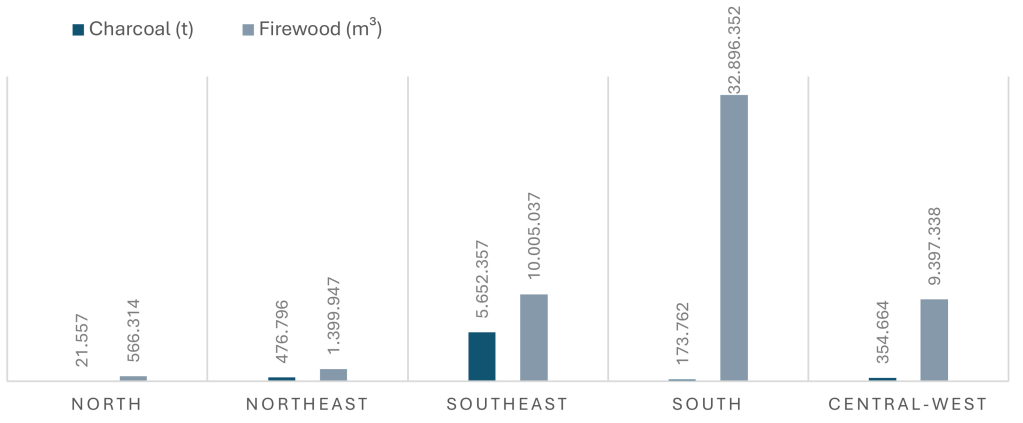


Figure 2 – Quantity produced in silviculture, by product and region of Brazil, 2024

Source: Adapted from IBGE, 2026.

Firewood consumption varies considerably across Brazil's regions and localities. Case studies compiled by Gioda (2019) reveal substantial differences in household firewood consumption, with reported values varying according to the local availability of the resource, the quality of the firewood used, the type and efficiency of cookstoves, the socioeconomic characteristics of households, and the geographic and climatic conditions of each region. For example, in small rural communities within the Northeastern Atlantic Forest, the average reported consumption was 686 ± 644 kg per person per year, illustrating the wide variation in regional estimates and the difficulty of establishing uniform national benchmarks. The persistence of this heterogeneity limits the effectiveness of policies based solely on national averages and underscores the need to complement them with regional and local assessments.

The choice between firewood and LPG in different contexts is not determined solely by monetary cost. Evidence suggests that the type of culinary activity also influences the selection of one fuel over the other. Gas stoves are predominantly used for quick-cooking

tasks, such as sautéing, grilling, preparing coffee and tea, and reheating previously cooked meals, whereas wood-burning stoves are commonly used for long-duration cooking, including the preparation of beans, Brazilian pine seeds (*pinhão*), potatoes, and cassava (Gioda, 2019). Firewood also offers the advantage of local availability in many regions, particularly where forest resources are located near households. This reduces its direct monetary cost and helps sustain its use among low-income families, even during periods of relative stability in LPG prices (Gioda, 2019).

The distinction between access to clean cooking technologies and the exclusive use of those technologies is particularly relevant in the Brazilian context. An EPE fact sheet notes that having access to clean cooking technologies does not necessarily mean that cooking is carried out exclusively with clean fuels. In 2022, 0.9% of Brazilian households reported cooking exclusively with biomass, while 16.3% reported using biomass in combination with other modern fuels, primarily LPG. This finding suggests that many households own an LPG stove but continue to rely on locally collected firewood as a strategy to reduce household energy expenditures. The concentration of biomass use for cooking among lower-income groups further underscores its association with economic vulnerability. In 2019, the poorest 50% of the Brazilian population accounted for approximately 80% of residential consumers who reported using biomass for cooking (EPE, 2024).

6.3. Implications for health, gender, and the environment

Household firewood use has interrelated effects on public health, gendered responsibilities, building energy performance, and regional ecosystems.

From a public health perspective, the combustion of solid fuels in rudimentary stoves, often lacking chimneys and installed indoors, produces smoke and soot that accumulate on household surfaces and degrade indoor air quality (Gomes, 2018; Gioda, 2019). The literature links this exposure to both respiratory and cardiovascular diseases, with particularly severe consequences for vulnerable populations. Global estimates indicate that household air pollution resulting from the use of solid fuels was associated with approximately 3.8 million premature deaths annually (Stoner et al., 2021). Within the household environment, women and children are considered especially vulnerable to several adverse health outcomes. Women are generally responsible for cooking activities and are therefore exposed more intensively to emissions from solid fuel combustion, whereas children are exposed during critical stages of development, potentially resulting in neurological impairments later in life (Su et al., 2024; Mani et al., 2026).

The energy performance of buildings plays an important role in shaping energy poverty, particularly with respect to thermal comfort, indoor air quality, and electricity con-

sumption for space conditioning. In Brazil, the regulatory framework is based on ABNT NBR 15575, the Performance Standard for Residential Buildings, which establishes minimum performance requirements for thermal, acoustic, and visual comfort, as well as durability, and on the Brazilian Building Energy Labeling Program (PBE Edifica), coordinated by the National Institute of Metrology, Quality and Technology (Inmetro), which classifies buildings according to the energy efficiency of their building envelope and building systems (ABNT, 2021). The Brazilian literature, however, indicates that a substantial proportion of social housing does not comply with the minimum requirements established by the standard, owing to low-cost construction solutions, building materials that are unsuitable for regional climatic conditions, and the absence of appropriately designed openings to promote cross-ventilation (Sorgato; Melo; Lamberts, 2014; Triana; Lamberts; Sassi, 2018). This performance deficit increases households' vulnerability to thermal discomfort, places additional demand on space-conditioning systems, and tends to be reflected in higher electricity consumption, thereby linking energy poverty to building design, construction practices, and the regulatory framework governing the built environment.

This relationship defines a specific field of action for civil engineering in addressing energy poverty. In the design and construction of social housing, the adoption of passive design strategies adapted to local climatic conditions, such as appropriate building orientation, window shading, cross-ventilation, and the specification of building envelope components suited to the corresponding bioclimatic zone, can simultaneously reduce thermal discomfort and the demand for mechanical heating and cooling, thereby directly lowering energy expenditures for low-income households (Sorgato; Melo; Lamberts, 2014; Triana; Lamberts; Sassi, 2018).

From this perspective, the requirements established by ABNT NBR 15575 and the PBE Edifica building energy labeling system can be viewed not only as mechanisms for regulatory compliance but also as instruments of housing policy aimed at promoting energy equity (ABNT, 2021). Incorporating minimum building envelope performance standards into public housing provision and housing improvement programs would help ensure that energy efficiency gains reach the most vulnerable households, those for which energy costs account for a disproportionate share of household income and in which building performance is generally most deficient (Triana; Lamberts; Sassi, 2018).

The phenomenon also exhibits pronounced gender dimensions. In rural areas of Brazil, firewood is generally collected manually within a radius of approximately 500 to 1,000 meters from households, with collection occurring one to three times per week. Women and children are typically the primary individuals responsible for this activity (Gioda, 2019). On average, women are estimated to spend 18 hours per week collecting and handling firewood, an activity that entails significant occupational risks, including

accidents and musculoskeletal disorders associated with carrying heavy loads. It also has broader social implications by reducing the time available for children's education and negatively affecting school attendance.

Culturally, responsibility for cooking within households also falls predominantly on women, resulting in greater exposure to toxic gases and particulate matter generated by the combustion of solid fuels. Recent studies suggest that this increased exposure may elevate the risk of cognitive impairment and sarcopenia (loss of skeletal muscle mass) (Su et al., 2024; Mani et al., 2026). This context reinforces the need for policies addressing energy poverty in Brazil to incorporate gender equity considerations, recognizing that the problem extends well beyond the mere physical availability of energy sources.

From an environmental perspective, the harvesting of firewood from native forests has significant implications across different Brazilian biomes. The Caatinga biome has already lost more than 50% of its original vegetation cover, with consequences for biodiversity, soil quality, hydrological regimes, and the advancement of desertification in semiarid regions. Santos and Gomes (2009) further reported that approximately 97% of the plant species used as energy sources in northeastern Brazil are harvested from native forests, whereas only 3% originate from reforestation areas or small-scale domestic woodlots.

Travassos and Souza (2014) argue that the reduction of forested areas in Brazil, particularly within the Caatinga, is historically linked to patterns of territorial occupation and the socioeconomic structure of the regions where it occurs. Consequently, this phenomenon extends beyond a purely energy-related perspective. Brito (2007) further emphasizes that, although the use of firewood in rudimentary cookstoves exhibits low thermal efficiency, providing only about one-tenth of the heat generation capacity of LPG stoves (EPE, 2023), wood biomass, when managed under appropriate and sustainable practices, may constitute a socially more equitable energy source, particularly because of its high capacity to generate employment per unit of financial investment. This observation highlights the need to distinguish, in discussions of policy responses, between the precarious household use of firewood associated with energy poverty and the potential sustainable utilization of forest biomass, a topic that will be revisited in the following section.

7. CHALLENGES AND FINAL CONSIDERATIONS

Analytical and policy challenges can be organized into two interdependent dimensions: gaps in definitions, data, and indicators; and policy responses, governance, and place-based action. Poorly designed policies reflect imprecise diagnoses, whereas diag-

noses detached from territorial contexts reproduce ineffective interventions (Gomes, 2018; Gioda, 2019).

The first dimension concerns the conceptual and methodological limitations involved in characterizing energy poverty in Brazil. As discussed in Section 4, the absence of a universally accepted definition means that the different approaches currently in use (threshold-based, relational, and multidimensional) each provide valuable insights while also presenting specific limitations (Bradshaw; Hutton, 1983; Boardman, 1991; Bouzarovski, 2014; Bouzarovski; Herrero, 2017). This conceptual ambiguity affects the selection of national indicators and complicates both longitudinal analyses and cross-jurisdictional comparisons. In the Brazilian context, although the official indicators associated with SDG 7 suggest a favorable performance at the aggregate level, they do not fully capture important dimensions of the phenomenon, such as the combined use of biomass and LPG, self-rationing of household energy consumption, service quality, the precariousness of electrical installations, thermal comfort, and territorial inequalities.

Similar gaps affect the monitoring of the use of traditional cooking fuels. Statistics on energy derived from firewood are difficult to obtain because of the diversity of end uses and the importance of informal production, particularly in regions where household consumption predominates (Gioda, 2019). Consequently, the literature frequently relies on localized case studies, especially from northeastern Brazil, which provide detailed descriptions of specific contexts but whose findings cannot be readily generalized to the country as a whole (Lopes; Canto, 2013; Chaves, 2016).

The second dimension concerns policy responses, which can be organized into three interrelated areas: sustainable forest biomass management, the transition to modern energy sources, and governance and financing mechanisms. The first area emphasizes the importance of sustainable forest management in the Caatinga biome, which offers the potential to reconcile energy production with environmental conservation in the territories where it is implemented (MMA, 2010; Lima Júnior et al., 2015). Initiatives involving environmental enforcement, forest management plans, and deforestation control programs have been associated with reducing pressure on forest ecosystems. Since 2018, federal funding calls supporting sustainable firewood production have provided financial assistance to farmers and small industries in the Caatinga through the National Forest Development Fund (FNDF) and the National Climate Change Fund (FNMC) (Gioda, 2019).

The second area focuses on expanding access to modern energy sources, including solar photovoltaic systems for isolated communities, wind energy in areas with favorable conditions, and biogas production from organic waste (IEA, 2025). These alternatives are consistent with Brazil's commitments to increase the share of renewable and

clean energy sources in its energy mix under the Paris Agreement, commitments that have been reaffirmed in subsequent official policy documents (MME; EPE, 2022).

The third area concerns the development of governance and financing mechanisms, including subsidies, tax incentives, affordable financing, payments for ecosystem services, and community capacity-building programs. The involvement of nongovernmental organizations (NGOs), local cooperatives, and territorial networks can complement these mechanisms, provided they are supported by appropriate institutional arrangements (MMA, 2010; Gioda, 2019). In this context, land tenure regularization and the enforcement of regulations against the illegal production and trade of forest products are essential components of sustainable governance. Taken together, these strategies underscore that addressing energy poverty requires coordinated action among different levels of government, local communities, civil society, and the private sector, in line with the principle of a just transition that underpins international debates on climate change and sustainable development (UN, 2021; IEA, 2025).

Transitioning to cleaner cooking is not merely fuel substitution; it is also a matter of public health, engineering, and housing design. Replacing firewood with LPG, electricity, or natural gas reduces risks associated with biomass combustion, but ventilation, smoke extraction, installation safety, and kitchen layout remain critical to indoor air quality. Accordingly, natural and mechanical ventilation, heating, ventilation, and air-conditioning (HVAC) and exhaust systems compliant with ABNT NBR 16401 (ABNT, 2008), and gas-appliance installations compliant with ABNT NBR 13103 (ABNT, 2020) are direct measures for mitigating household cooking risks.

Brazil's favorable aggregate SDG 7 performance should therefore be interpreted cautiously. High electricity and clean-cooking access and a renewable-intensive energy supply coexist with persistent energy poverty among vulnerable groups, monitoring gaps, and environmental pressures from traditional fuels. An effective response requires better definitions and indicators, regionally calibrated policies, stronger governance and financing, and integration of the social, environmental, health, and economic dimensions of sustainable development—one of the central purposes of the 2030 Agenda.

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CHAPTER 2

Construction and the 2030 Agenda: integrating urban redevelopment, social housing, urban mobility, and digital tools

Ana Paula Branco do Nascimento, Rafael Franklin da Silva Ferreira, Gabriel Miranda Santanna, Victor Agostinho Conceição, Thais Reis Silva Rocha, Jorge Luis Gallego Zapata

1. INTRODUCTION

The construction industry holds a strategic position in urban and territorial development due to its capacity to transform the built environment, drive economic growth, and directly influence the environmental and social quality of cities. However, the sector is also among the largest consumers of natural resources and generators of waste and emissions, making it essential to incorporate sustainability principles into every stage of the building life cycle.

In this context, the 2030 Agenda for Sustainable Development represents a transformative vision that integrates these dimensions and guides countries toward a new development paradigm based on equality, resilience, and sustainability (Naciones Unidas, 2018). More than a decade after its adoption, and with the midpoint of its timeframe now passed, it is essential to critically assess its progress and shortcomings, particularly in resource-intensive sectors such as construction.

Population growth, intensifying urbanization, rising demand for infrastructure, and the housing deficit heighten the need for construction practices that are more sustainable, resilient, and aligned with the global guidelines of the 2030 Agenda (Lima; Chiroli; Zola, 2025). In this regard, the Sustainable Development Goals (SDGs) provide a guiding framework for the sector's transformation, promoting solutions that balance urban development, quality of life, and environmental preservation.

Global population growth and the accelerated pace of urbanization pose new challenges to urban planning. According to the United Nations (UN), the world population reached 8.2 billion in 2025, of which about 45% live in cities and 35.6% in small urban centers, whereas 19.6% remain in rural areas. Projections indicate that urbanization will continue over the coming decades: by 2050, approximately two-thirds of global population growth is expected to occur in cities, and most of the remaining growth is expected to be concentrated in small urban centers (UN, 2025).

This scenario highlights the need to rethink the capacity of cities to provide, in an integrated and sustainable manner, housing, mobility, water, energy, food, infrastructure, and ecosystem services, reconciling population growth with environmental conservation and quality of life. In this context, urban planning strategies that consider the relationship between population density, land use, and environmental conservation become relevant (Wang et al., 2025).

In the field of civil engineering, sustainability requires integrated, systemic approaches that consider the entire life cycle of the built environment (Kellett, 2015). This encompasses everything from land-use planning and the redevelopment of degraded areas to housing development, urban mobility, and infrastructure management. Furthermore, the incorporation of digital technologies and decision-support tools has enhanced the capacity to plan and execute more efficient and sustainable projects.

Against this backdrop, this chapter presents key contributions to professional practice derived from dissertations developed within the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu. The studies address the redevelopment of contaminated sites, sustainable affordable housing, urban mobility, and resilient infrastructure, as well as the use of Building Information Modeling (BIM) as a tool to support sustainability. The contributions are organized according to a progressive logic (Figure 1): starting with territorial redevelopment, moving on to sustainable housing production, urban infrastructure, and mobility, and concluding with the integration of these dimensions through digital tools applied to the construction sector.

This integrated approach demonstrates the contribution of applied research to professional practice, strengthening the construction sector as a strategy for promoting sustainable urban development and achieving the 2030 Agenda goals. The studies highlight the importance of aligning resilience strategies with the SDGs, particularly SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

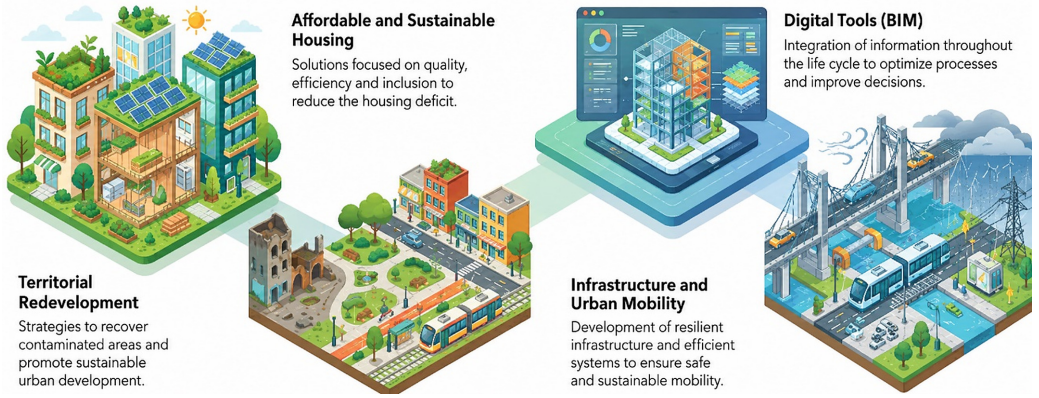


Figure 1 – Themes of the studies included in this chapter, which form part of the engineer's professional practice, focusing on new construction technologies and alignment with the 2030 Agenda to promote the population's quality of life.

Source: Prepared by the authors based on the themes of the four dissertations discussed in this chapter and with the support of NotebookLM, 2026.

2. REDEVELOPMENT OF CONTAMINATED AREAS AS AN URBAN SUSTAINABILITY STRATEGY

Rapid urban growth, coupled with a scarcity of land available for expansion in established metropolitan regions, has intensified the need for more efficient strategies for urban land use and development. In this context, the reuse of contaminated sites emerges as an alternative for urban sustainability by enabling the reintegration of underutilized areas into the urban fabric. This approach contributes to the revitalization of degraded areas, the reduction of urban sprawl, and the improvement of environmental quality in cities (Ferreira; Nascimento; Yoshikawa, 2022).

More than just a technical solution for environmental liabilities, the reuse of these areas can be understood as part of urban redevelopment strategies. The analysis of expert perceptions indicates that projects involving contaminated sites have the potential to integrate environmental, economic, and urban planning aspects, particularly in metropolitan contexts such as São Paulo (Ferreira, 2023). In this regard, the viability of such projects is directly linked to the ability to integrate contaminated site management with real estate market demands and urban development guidelines; the literature frequently identifies regulatory predictability, clear technical criteria, and proper risk management as critical factors for decision-making and project feasibility.

In the Latin American context, contaminated site management remains constrained by regulatory gaps, fragmented norms, and a lack of systematic inventories, which hinders integration into sustainable urban planning (España et al., 2018). Furthermore, the issue of urban soils extends beyond specific contaminated sites to encompass diffuse contamination processes linked to urban dynamics, affecting even public spaces such as parks and green zones. Urban soils subjected to anthropogenic pressures undergo significant changes in their physical, chemical, and biological properties and can accumulate potentially toxic elements in considerable concentrations, with measurable ecotoxicological effects, which compromises their ecological functionality and the provision of ecosystem services and poses distinct risks to vulnerable populations (Gallego et al., 2025; Moreno-Ríos et al., 2026). In this scenario, the absence of structured monitoring systems and spatial databases limits the identification of priority areas for intervention and the incorporation of such data into urban planning instruments. This gap reduces the effectiveness of redevelopment strategies, as decision-making continues to rely on incomplete information, especially in complex urban settings. Thus, the redevelopment of contaminated areas must be understood within a broader approach to urban land management, one that integrates environmental monitoring, risk assessment, and spatial planning, thereby enabling a shift from isolated interventions to integrated urban sustainability strategies.

Beyond environmental benefits, the redevelopment of contaminated sites contributes to improving the population's quality of life by enabling the creation of new housing, commercial, and service developments in areas with established infrastructure. This reuse of urban land reduces travel, enhances mobility, and helps lower urban transport-related emissions, thereby reinforcing territorial sustainability, consistent with recent studies showing reduced travel demand and transport emissions in brownfield[1] redevelopment projects within established urban areas (EPA, 2024). Positive impacts are also observed in the appreciation of surrounding property values, job creation, and the economic revitalization of rehabilitated areas, as noted by experts (Ferreira et al., 2023).

From a construction industry perspective, the redevelopment of these areas represents an opportunity for sustainable real estate development while simultaneously contributing to the mitigation of historical environmental liabilities. However, the literature highlights significant technical and institutional challenges, including regulatory barriers, uncertainties regarding environmental liability, and remediation costs, which are widely discussed in international research on brownfields (McCarthy, 2002; He; Zainol; Azali, 2024b). Furthermore, in the Brazilian context, studies indicate that factors such as

[1] In an international context, contaminated areas are frequently classified as brownfields, defined as properties whose development, redevelopment, or reuse is hindered by the actual or potential presence of hazardous substances, pollutants, or contaminants (EPA, 2024).

legal certainty, regulatory predictability, and risk management are decisive for the viability of these projects (Ferreira, 2023). On a technical-operational level, key challenges include the need for accurate environmental assessments and the appropriate definition of remediation strategies, aspects extensively discussed in the literature on contaminated site management (NRC, 2013). These factors necessitate the involvement of multidisciplinary teams and specialized professionals, underscoring the importance of technical expertise in managing such areas.

Another relevant aspect concerns the relationship between the redevelopment of contaminated sites and the SDGs. Reusing these areas contributes notably to SDG 11 by fostering more inclusive, resilient, and sustainable cities; it also intersects with SDG 3 (health and well-being) and SDG 6 (protection of water resources). In this context, studies indicate that the environmental remediation of these sites reduces risks to human health and improves urban environmental conditions (He; Zainol; Azali, 2024a). Such remediation is recognized as a key strategy for urban sustainability and, specifically in Brazil, as an opportunity to integrate environmental recovery with real estate development in metropolitan areas (Ferreira, 2023).

Thus, the redevelopment of contaminated sites serves as a strategic tool for sustainable construction by integrating environmental remediation, real estate development, and the enhancement of urban space. This territorial approach lays the groundwork for sustainable housing production, as discussed in the following section, highlighting the importance of reusing urban land as a starting point for fostering more sustainable cities.

In this regard, making redeveloped sites available in areas already equipped with urban infrastructure creates favorable conditions for developing more sustainable housing projects, reinforcing the importance of coordinating territorial planning with housing production within the construction sector.

3. UPGRADING OF SOCIAL INTEREST HOUSING (HIS) PROJECTS ALIGNED WITH THE SDGS

Improving the quality of HIS represents one of the construction industry's key challenges within the context of sustainable development. The housing deficit, coupled with unplanned urban expansion and the occupation of environmentally fragile areas, underscores the need for higher-quality housing projects capable of integrating environmental sustainability, construction quality, and social inclusion.

The study by Santanna (2024) incorporated sustainability guidelines into the housing design process to help improve living conditions and promote more sustainable cities. The use of technical specifications aligned with the SDGs enabled the development of more

flexible and functional architectural solutions, focusing on spatial quality and adaptability to user needs. Adopting sustainable design strategies also aimed to minimize the need for post-occupancy interventions, thereby preventing inappropriate modifications resulting from informal self-building.

First, the definitions and conditions for "Housing Deficit" and "Housing Inadequacy" established by the João Pinheiro Foundation were examined: the former refers to dwellings that need to be built or replaced, whereas the latter refers to those requiring interventions to improve their quality (FJP, 2021). An assessment of the SDGs and their respective targets established a link between these concepts and SDG 1 (No Poverty) and SDG 11 (Sustainable Cities and Communities) (Santanna; Nascimento; Yoshikawa, 2023).

Given that low-income populations are directly affected by a lack of access to quality housing, the principles of SDG 1 support socioeconomic advancement and the consequent increase in the purchasing power of the most disadvantaged classes, thereby enabling them to access the basic means of human dignity defined by the 1988 Constitution (Brasil, 1990). Housing improvement, in turn, aligns with SDG 11 through the enhancement of urban infrastructure, encompassing both the dwellings themselves and their surrounding areas. Batista et al. (2022) emphasize that both the increase in the purchasing power of low-income populations and the expansion of housing depend on state action.

In this context, a practical case study was conducted on a 14 m² HIS architectural project developed in 2021 by the Department of Housing of Suzano, in the São Paulo Metropolitan Area (Figure 2). After instances of housing inadequacy were identified, an alternative floor plan was drafted, aiming to apply design best practices found in the literature and to align the project thematically with the aforementioned SDGs 1 and 11.

As a result, four architectural designs were developed, expandable across three phases, using BIM tools (Figure 3). The first implementation phase would begin with a social housing unit limited to 60 m², in which the layout of rooms and furniture was guided by concepts of flexibility and functionality found in the literature and technical specifications were derived from relevant standards; the second phase would involve constructing a rear room, bringing the total area to 87.50 m²; finally, the third phase would entail installing stairs to enable the project's expansion to an upper floor (Santanna, 2024).

The advantages of applying BIM tools to the development of more sustainable housing underscore the importance of digitalization in the construction industry. By consistently working in 3D, BIM facilitates visualization and understanding for various stakeholders while providing an integrated, interoperable foundation that enhances the identification of clashes and incompatibilities during the design phase itself. This approach contributes to optimizing the design process, improving building performance, and re-

ducing waste, while also facilitating life cycle analysis of the housing units (Adejola; Nwobodo-Anyadiegwu, 2025).

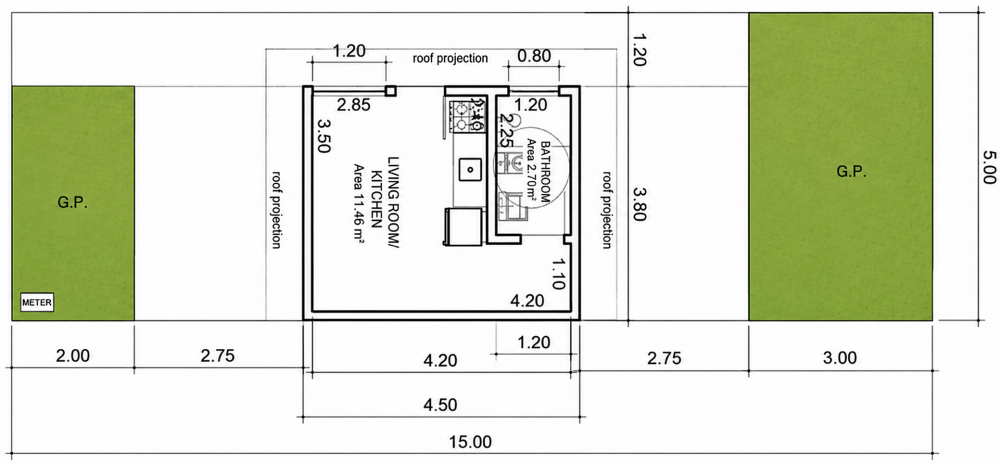


Figure 2 – Original architectural design

Source: Suzano Department of Housing, 2021.

By contrast, investigations into the original architectural project revealed a context of scarcity within the public sector: stakeholders with divergent goals, decentralized decision-making, and low financial investment converged on a 14 m² design (reflecting extreme cost-cutting measures), contrasting sharply with the initial 60 m² proposed in this study. Thus, Santanna (2024) highlights the need for effective structuring within the public sector to achieve tangible results in addressing the housing crisis.

For the proposed architectural project, the concept of planned expansion aligns with the residents' increased purchasing power (SDG 1) and the orderly modification of space (SDG 11). Beyond the housing itself, recent literature demonstrates that the provision of HIS should incorporate criteria related to environmental performance, energy efficiency, accessibility, urban infrastructure, and social inclusion. In this regard, housing planning must consider the urban integration of the homes, ensuring adequate infrastructure and promoting quality of life for the population.

From this perspective, housing serves as an instrument for implementing the SDGs by simultaneously contributing to the reduction of inequalities, the improvement of quality of life, and sustainable urban development, representing a fundamental step toward building more resilient and inclusive cities. The integration of territorial redevelopment and housing production highlights a systemic approach to sustainable construction, which subsequently extends to discussions on urban infrastructure and mobility, elements essential for

the sustainable functioning of cities. Ultimately, the quality of housing also depends on the urban infrastructure to which it connects.



Figure 3 – Architectural models proposed by Santanna (2024).

Source: Santanna, 2024.

4. URBAN MOBILITY AND RESILIENT INFRASTRUCTURE IN SUSTAINABLE CONSTRUCTION

Urban sustainability requires that housing investments be accompanied by safe, efficient, and resilient mobility systems. Climate change, which has intensified in recent decades, makes sustainable transport a necessity in cities (Anastasiadou; Gavanas, 2025). However, according to Ayan, Bell, and Dissanayake (2025), many of these systems fail to meet user needs. Furthermore, increasing the demand for urban rail transport systems is essential to achieving global CO_2 emission reduction targets in alignment with the SDGs of the 2030 Agenda.

Public transport plays a vital role in urban planning, affecting the quality of life of millions of people, particularly in metropolitan regions. As cities grow, the demand for sustainable mobility solutions becomes increasingly urgent, driving the development of metro and rail systems. These systems can alleviate congestion, reduce greenhouse gas emissions, and improve accessibility in large cities (Chiquetto et al., 2024; Zhang et al., 2024; Abhijna et al., 2025). However, their implementation and operation present challenges regarding infrastructure maintenance and safety.

Urban sustainability depends on the quality and resilience of mobility infrastructure, especially regarding the transport systems that underpin city operations. In this context, the management of major engineering structures (*obras de arte especiais*, OAEs), such as bridges, viaducts, and railway structures, plays a strategic role in ensuring the safety, durability, and efficiency of the urban system. A preventive approach to maintaining these structures contributes not only to operational safety but also to the environmental and economic sustainability of the construction sector.

Structured inspection procedures, guided by technical standards, should be viewed as strategic asset management tools rather than merely regulatory requirements (Rocha, 2026). Systematizing inspections enables the early identification of anomalies and the reduction of structural risks, and guides preventive maintenance planning. This approach extends the service life of structures and avoids emergency interventions, which typically entail higher consumption of materials and financial resources.

From a sustainability perspective, experts consider the preventive maintenance of existing infrastructure to offer significant advantages over replacing degraded structures (Rocha, 2026). Extending the service life of OAEs reduces the need for demolition and reconstruction, thereby minimizing waste generation and the consumption of construction materials. This strategy aligns with circular economy principles and the reduction of environmental impacts associated with large-scale construction projects.

Another relevant aspect concerns the need for integration among inspection, data management, and decision-making. Fragmented information regarding the condition of structures has been identified as a major challenge for the efficient management of OAEs. In this context, the adoption of integrated asset management platforms represents a significant practical contribution, enabling historical traceability, risk-based prioritization, and greater transparency in investment decisions. Such integration fosters the economic sustainability of infrastructure and contributes to more efficient resource allocation.

4.1. Management of OAEs in São Paulo from a sustainability perspective

An analysis of responses from engineering experts with over 10 years of experience in the inspection and maintenance of OAEs indicates that improving OAE management in the city of São Paulo extends beyond operational dimensions; it represents a structural challenge involving technical and institutional governance, as well as technological hurdles. The results were organized into two categories: (1) institutional strengthening and technical governance, and (2) urban sustainability and management modernization.

Regarding Category 1, there is a consensus on the need for specialized training, the consolidation of asset inventories, and the strengthening of legal mechanisms for oversight and transparency. These aspects align directly with the SDGs, specifically SDGs 4, 9, and 16, by underscoring the importance of professional qualifications and reliable information regarding OAE management. This perspective is supported by the literature, which identifies the lack of structured asset management systems as a major barrier to infrastructure efficiency in complex urban settings, particularly in Latin American cities (Cardoso et al., 2012). Furthermore, making decisions based on technical criteria rather than partisan political priorities emerges as an essential condition for institutional sustainability and the rational use of public resources.

In Category 2, results indicate that fostering a culture of preventive maintenance, combined with the use of digital technologies and the integration of information systems, serves as a strategic driver for the sustainability of OAEs in the municipality of São Paulo. Prioritizing preventive maintenance, which aligns with SDG 12, proves to be not merely a technical practice but also an environmental and economic strategy; preserving existing structures reduces the need for reconstruction and, consequently, lowers emissions associated with the infrastructure's life cycle.

Furthermore, the integration of tools such as BIM, sensors, and intelligent monitoring systems, aligned with SDG 9, enhances management and decision-making efficiency; studies demonstrate that digitalization reduces waste and improves the performance of urban systems (Adejola; Nwobodo-Anyadiegwu, 2025). In this context, the functional safety of

structures and its link to sustainable urban mobility (SDG 11) underscore the role of OAEs as central elements of urban quality of life. Similarly, Frangopol and Liu (2007) highlight that urban infrastructure resilience is directly linked to data-driven management and the adoption of preventive strategies, corroborating the empirical findings of this study. Thus, the management of OAEs in São Paulo represents a strategic area for promoting urban sustainability by integrating technical, institutional, and socioenvironmental dimensions.

Consequently, the research highlights the importance of specialized technical training in structural monitoring, structural pathology, and asset management. A shortage of qualified professionals compromises inspection quality and, by extension, the efficiency of preventive maintenance. Therefore, technical training and the development of specific competencies are essential for the sustainability of urban infrastructure. Professional qualification is a foundational requirement and relates directly to SDG 4.

There is a consensus regarding the shortage of skilled professionals, the market's rapid growth, and the need for specific training in inspection and asset management; without investment in qualified human capital, the system becomes vulnerable. Furthermore, there is considerable potential for incorporating digital technologies into the management of OAEs, including the use of drones for inspections, the digitization of reports, integration with BIM models, and the development of predictive degradation indicators. These tools contribute to modernizing professional practice and expanding the capacity for sustainable planning regarding mobility infrastructure.

The integration between infrastructure management and the SDGs is also evident, particularly regarding SDG 9, which addresses the construction of resilient infrastructure, and SDG 11, focused on safe and sustainable cities. Thus, urban mobility and the maintenance of existing structures are fundamental elements of sustainable construction, broadening the discussion initiated with territorial redevelopment and social housing. The management of these structures increasingly relies on the incorporation of digital technologies.

5. BIM AS AN INTEGRATING TOOL FOR SUSTAINABLE CONSTRUCTION

Among these technologies, BIM stands out for integrating information throughout the entire life cycle of projects. BIM enables the modernization of decision-making processes by allowing for the simulation of construction scenarios and the anticipation of environmental impacts. This capability facilitates the definition of strategies aligned with the SDGs, while also enhancing project predictability and reducing uncertainties during the construction process (Conceição, 2025; Conceição et al., 2025). Digital modeling also

allows for the assessment of energy performance, material consumption, and environmental impacts as early as the design phase.

Among the emerging technologies applied to the sector, BIM stands out as an approach capable of integrating information throughout the entire life cycle of projects (Abdelrheem; El-Helloty; Ehab, 2025). Recent studies indicate that BIM serves as a platform to support decision-making, enabling simulations, analyses, and greater planning precision, thereby contributing to project efficiency and sustainability (Pavón et al., 2025).

Figure 4 presents the distribution of SDGs in research linking BIM and sustainability in the construction industry. It summarizes the presence of SDGs across the 20 analyzed articles (the 10 most cited and the 10 most recent). Analysis of the chart reveals a predominance of SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities), indicating that the literature has prioritized infrastructure modernization and sustainable urban planning. This result reinforces the role of BIM as a tool supporting technological innovation and the efficient management of built assets.

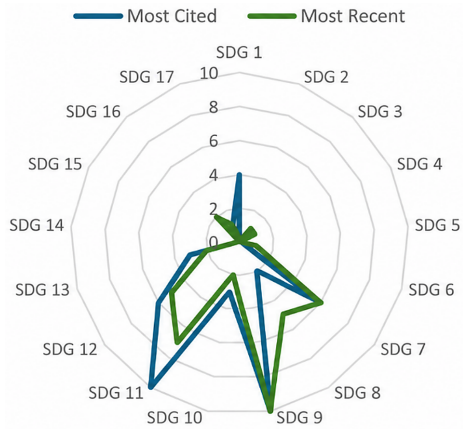


Figure 4 – Distribution of SDGs in BIM research in the construction industry.

Source: Conceição et al., 2025.

The relevance of SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production) is evident, particularly in recent studies, indicating a trend toward expanded research focused on energy efficiency and waste reduction. Recent works demonstrate that BIM enables energy performance simulations and more efficient planning of material use, contributing to more sustainable construction practices (Veerendra et al., 2025; Teng; Shen; Tutuko, 2025; Lau et al., 2025).

From a professional practice perspective, BIM contributes to improved planning, reduced rework, resource optimization, and higher project quality. Its application facilitates

data-driven decision-making and integration among various stakeholders in the construction process, contributing to projects that are more efficient and aligned with the 2030 Agenda guidelines (Zapp; Magalhães; Scheer, 2024). Additionally, integration with emerging technologies enhances its monitoring, traceability, and predictive analysis capabilities, reinforcing its role as a strategic tool in sustainable construction (Abdelrheem; El-Helloty; Ehab, 2025; Nguyen; Ahn; Kim, 2025).

Thus, BIM establishes itself as a significant tool for promoting sustainability in the sector by integrating technological innovation with efficient resource management. Although gaps remain, particularly regarding broader social and environmental dimensions, its application potential points to a promising path for developing construction practices aligned with the 2030 Agenda.

6. FINAL REMARKS

The contributions presented throughout this chapter demonstrate the strategic role of civil engineering in promoting sustainable development, especially when aligned with the guidelines of the 2030 Agenda. The integrated analysis of the dissertations revealed that sustainable construction must be understood through a systemic approach aligned with the SDGs of the 2030 Agenda. This approach is structured around territorial redevelopment, sustainable low-income housing, resilient infrastructure and mobility, and the incorporation of digital tools for decision-making.

At the territorial level, the redevelopment of contaminated sites emerges as a fundamental element for efficient urban land use, contributing not only to environmental remediation but also to the restructuring of the urban fabric and the curbing of uncontrolled urban sprawl. This strategy lays the groundwork for urban sustainability by enabling the reuse of underutilized areas and their reintegration into regions with established infrastructure, thereby strengthening the link between urban planning and sustainable construction. Furthermore, it is essential to consolidate institutional frameworks and governance mechanisms that reduce regulatory uncertainty and foster collaboration between public and private stakeholders. Such measures are necessary to enable redevelopment at scale and to incorporate both historical environmental liabilities and diffuse degradation processes into sustainable urban development strategies.

In turn, sustainable low-income housing demonstrated significant potential for reducing socio-spatial inequalities and improving living conditions. Incorporating SDG-aligned guidelines, combined with the use of digital tools and integrated planning of the surrounding urban environment, highlights that housing quality must be understood in a

broader sense, encompassing not only the building itself but also urban infrastructure, services, and the territorial integration of the housing units.

Urban mobility and resilient infrastructure were presented as essential elements for the sustainable functioning of cities. Preventive management of OAEs, based on structured inspections and maintenance planning, contributes to extending the service life of structures, reducing environmental impacts, and optimizing resources. This approach reinforces the importance of sustainability in existing infrastructure, avoiding emergency interventions and promoting greater efficiency in the management of the built environment.

BIM has been identified as an integrating tool for sustainable construction, enabling coordination among territorial planning, housing design, infrastructure management, and building operations. Digital modeling contributes to waste reduction, improved design quality, interdisciplinary integration, and the assessment of the construction life cycle. Thus, BIM establishes itself as a strategic instrument for implementing sustainable practices in the construction industry.

Collectively, the analyzed dissertations demonstrate that sustainability in construction does not stem from isolated interventions but from the integration of territorial planning, housing quality improvements, resilient infrastructure management, and technological innovation. By bridging applied research and professional practice, the Professional Master's Program in Civil Engineering shows its contribution to addressing contemporary urban challenges and implementing the 2030 Agenda, reinforcing the role of civil engineering as an agent of transformation in building more resilient and sustainable cities.

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CHAPTER 3

Artificial intelligence applications in civil engineering: an exploratory systematic review

José Carmino Gomes Jr., Roberta Giraldi Romano, Dimas Alan Strauss Rambo, Guilherme Leite Gaudereto, Carlos Alberto Cioce Sampaio, Ailton José dos Santos, Guilherme da Silva Leme, Denis Becker

1. INTRODUCTION

1.1. Background

The construction industry has undergone a continuous process of technological transformation, driven by the digitalization of processes and the incorporation of technologies associated with Construction 4.0. This movement involves the integration of resources such as Building Information Modeling (BIM), digital twins, the Internet of Things, computer vision, cyber-physical systems, and artificial intelligence (AI), with the aim of increasing efficiency, productivity, safety, and sustainability in the built environment (Baduge et al., 2022). In this context, AI plays a strategic role by enabling workflow automation, the processing of large volumes of data, and decision support at different stages of the life cycle of buildings and infrastructure (Mishra et al., 2024).

From a philosophical perspective, civil engineering has always represented the materialization of culture, rationality, and human triumph over the forces of nature. With the advent of these technologies, the built environment ceases to be a passive and inert receptacle; it begins to act as a dynamic cybernetic entity capable of "learning," reacting, and anticipating phenomena. This imposes a profound reconsideration of what it means to inhabit and design our shared spaces.

Digital transformation in civil engineering is not limited to the isolated adoption of computational tools. It is a broader change in the way data, models, processes, and

decisions are integrated. From conceptual design to the operation and maintenance of infrastructure, AI has been associated with pattern identification, the construction of predictive models, support for decision systems, and the integration of information from sensors, images, simulations, BIM platforms, and operational databases (Manzoor et al., 2021; Baduge et al., 2022).

Recent literature points to a gradual transition from traditional empirical methods to models based on machine learning and deep learning, particularly for problems characterized by nonlinearity, uncertainty, and large volumes of data (Kuruvachalil et al., 2025). In different subfields of civil engineering, such as construction materials, structures, geotechnical engineering, urban planning, infrastructure, and logistics, AI techniques have been used to predict performance, optimize resources, monitor operational conditions, and support technical and managerial decisions (Hoang; Pham, 2016; Aslam et al., 2020; Bai et al., 2020; Koumetio Tekouabou et al., 2022; Deineko; Jungnickel; Kehrt, 2024).

Another relevant line of development is the advancement of approaches that integrate data-driven models with physical knowledge and technical domain expertise. Physics-informed machine learning (PIML), for example, has been discussed as an alternative for reducing the limitations of purely data-driven models, especially in structural health monitoring and the life-cycle management of bridges and critical infrastructure (Sun et al., 2026). This trend reinforces the need to understand not only which AI techniques are used but also how these techniques relate to specific civil engineering problems.

1.2. Research problem

The expansion of AI applications in civil engineering has occurred heterogeneously, distributed across different disciplinary domains, computational techniques, databases, and application purposes. This fragmentation makes it difficult to build an integrated view of AI's role in civil engineering and its contribution to the life cycle of buildings and infrastructure. Previous reviews indicate that research still occurs, in many cases, in a segmented manner, with limited integration among areas, processes, and stages of application (Deineko; Jungnickel; Kehrt, 2024; Mishra et al., 2024).

In addition to fragmentation, challenges related to data quality, availability, and uncertainty persist. Incomplete databases, noisy sensor data, scale limitations, and a lack of standardization may compromise model performance and generalization, particularly in infrastructure and public management contexts (Kuruvachalil et al., 2025). This is compounded by the problem of interpretability, because many high-performance models, especially those based on deep learning, operate as systems that are difficult to explain,

which may reduce their acceptance in engineering decisions that require transparency, traceability, and technical responsibility (Putra; Rokade, 2025).

A gap can also be observed between the academic development of models and their large-scale adoption in the construction industry. Although the literature presents relevant advances, transferring these models to professional routines, corporate systems, infrastructure agencies, and regulatory processes still requires greater methodological integration and validation in real-world contexts (Mishra et al., 2024).

Given this scenario, the problem guiding this review is to understand how AI has been applied in civil engineering and the extent to which recent literature makes it possible to identify patterns of use, contributions, recurring limitations, and research opportunities. Simply increasing the number of studies does not ensure an integrated understanding of the field, especially when applications remain distributed across different subfields, techniques, and databases.

1.3. Rationale

This research is justified by the need to systematize scientific production on AI applications in civil engineering in order to provide an overview that supports the identification of gaps, trends, and research opportunities. The diversity of techniques, application areas, and purposes of use calls for an analysis that articulates primary studies with previous reviews, without conflating direct evidence of application with previously published secondary syntheses. This rationale is further supported by the close relationship among AI, sustainability, and infrastructure resilience. According to the literature, intelligent models can optimize resource use, reduce costs, improve maintenance processes, and foster more proactive management of construction and urban systems (Manzoor et al., 2021). Moreover, in smart-city contexts, models based on textual data, natural language processing, and time-series forecasting can support the dynamic identification of residents' demands and improve data-driven urban governance (Zhang et al., 2025). In this regard, synthesizing the applications, limitations, and opportunities related to AI in civil engineering is relevant not only to understanding the current state of research but also to supporting new academic work, particularly in scientific supervision, undergraduate research, final projects, and graduate studies.

This urgency is further reinforced by the country's current science and education policies, which support the integration of AI into research and technological development at both the graduate and basic education levels. Brazil's new National Education Plan (Law No. 15,388/2026) underscores this cross-cutting priority by establishing national guidelines for the adoption and use of digital educational platforms and AI in

education, while ensuring data protection, transparency, and strictly pedagogical purposes (Brasil, 2026).

In the academic and scientific context, the National Graduate Education Plan (PNPG 2025–2029) emphasizes that the education of master's and doctoral graduates must be dynamic and aligned with constant global digital transformations, which requires the mandatory inclusion of learning competencies and skills in high-impact innovations such as big data and AI. In addition, the "National Agenda for the Education of Higher-Level Personnel" (2025) identifies AI and data science (Macrotheme 4) as fundamental pillars, demonstrating that these technologies are essential for transforming data into applicable knowledge, fostering innovation in engineering and other sectors, and guiding evidence-based decisions, thereby generating direct value for the public and private sectors (CAPES, 2025, 2026).

This review offers both an analytical contribution and educational value within the Graduate Program in Civil Engineering, providing an initial systematization of topics, gaps, and methodological challenges that supports the delimitation of research problems, the supervision of master's students, and the development of investigations applied to the built environment. By organizing techniques, application areas, limitations, and gaps related to the use of AI in civil engineering, the study provides support for defining research topics, delimiting problems, selecting methods, and developing investigations aligned with contemporary demands in the field.

1.4. Objectives

1.4.1. General objective

To analyze, through an exploratory systematic review based on the Scopus database, the main applications of AI in civil engineering, identifying the techniques employed, application areas, practical contributions, limitations, and research opportunities.

1.4.2. Specific objectives

- To identify the main AI techniques applied to civil engineering.
- To map the areas of civil engineering in which AI has been applied.
- To analyze the practical contributions of AI to performance prediction, process automation, decision support, cost reduction, productivity, and risk mitigation.
- To examine the limitations and challenges associated with the use of AI in civil engineering, including data availability and quality, model interpretability, result validation, and integration with professional practices.

- To systematize research gaps and future development opportunities related to the application of AI techniques to civil engineering problems.

1.5. Research questions

1.5.1. Main research question

What are the main applications of AI in civil engineering identified in the scientific literature, considering the techniques used, application areas, practical contributions, limitations, and research opportunities?

1.5.2. Specific research questions

- Which AI techniques have been used in studies applied to civil engineering? (RQ1)
- In which areas of civil engineering has AI been applied? (RQ2)
- What practical contributions does AI offer for performance prediction, process automation, decision support, cost reduction, productivity, and risk mitigation? (RQ3)
- What are the main methodological limitations and challenges associated with applying AI in civil engineering? (RQ4)
- What gaps and research opportunities are identified in the literature on the use of AI in civil engineering? (RQ5)

2. EXPLORATORY SYSTEMATIC REVIEW METHOD

This section presents the methodological procedures adopted to conduct the exploratory systematic review. The review report was guided by the PRISMA 2020 recommendations, which establish guidelines for the transparent, complete, and accurate reporting of systematic reviews (Page et al., 2021). Based on this guidance, the type of review and its rationale, the eligibility criteria adopted, the information sources and search strategy, the study-selection process, the data-extraction procedures, and the strategy for analyzing and synthesizing the results are presented. The complete screening, data-extraction, and methodological-assessment matrices were made available in a supplementary repository to preserve the traceability and transparency of the process without compromising the flow of the main text: https://www.gomesjc.com.br/revisoes/ia-engenharia-civil/.

This research is characterized as an exploratory systematic literature review focused on the applications of AI in civil engineering. The choice of this approach is justified by the interest in mapping, organizing, and analyzing techniques, application areas, contributions, limitations, and research gaps identified in the scientific literature.

Although the study adopts systematic procedures for searching, selection, screening, extraction, and synthesis, its scope was limited to the Scopus database, selected for its coverage of scientific journals, conference proceedings, and academic publications indexed in different fields of knowledge, including civil engineering, construction, infrastructure, technology, data science, and AI. The review therefore has an exploratory nature, as it seeks to offer a structured and analytical view of the studies retrieved from this database without claiming to exhaust all scientific production available from other academic sources.

No fixed time frame was defined for the search. This decision was intended to allow the retrieval of studies published in different periods, considering the evolution of the use of AI in civil engineering. The search began on April 30, 2026, and ended on May 1, 2026.

The search strategy was structured by combining terms related to AI and civil engineering. Terms associated with computational techniques were considered, such as artificial intelligence, machine learning, deep learning, neural networks, data mining, predictive models, hybrid models, and optimization algorithms, together with terms referring to the field of application, such as civil engineering, construction, infrastructure, structures, geotechnics, construction materials, transportation, sustainability, BIM, and construction management.

The search strings were applied in the Scopus database to the title, abstract, and keyword fields, according to the database's own syntax. Owing to the chapter's length limitation, the complete search strings were made available in the review's supplementary repository.

As an operational eligibility criterion, only records whose full text was available through open access were considered, because a complete reading was required to confirm relevance to the topic, verify the nature of the study, and extract methodological and analytical data.

Studies addressing applications of AI in civil engineering, construction, or fields directly related to the built environment were included. This delimitation encompassed studies focused on problems of design, execution, operation, maintenance, performance, safety, sustainability, infrastructure, and decision-making within contexts specific to civil engineering.

In terms of methodology, eligibility also extended to studies employing AI-related techniques, including machine learning, artificial neural networks, deep learning, optimization algorithms, data mining, predictive models, hybrid models, computer vision, decision-support systems, and related approaches. The central criterion was the presence

of an application or methodological analysis linked to the use of these techniques in problems pertinent to civil engineering.

The inclusion criteria covered studies applied to different areas of civil engineering, such as construction materials, structures, geotechnical engineering, transportation, construction management, sustainability, infrastructure maintenance, construction planning, urban planning, water resources, urban infrastructure, and monitoring of construction systems. Priority was given to studies presenting results related to performance prediction, decision support, process automation, cost reduction, increased productivity, risk mitigation, optimization, or improvement of technical and managerial processes.

Regarding publication type, scientific articles published in journals, conference proceedings, or recognized academic databases and written in Portuguese, English, or Spanish were included. No fixed time frame was applied to the search, although the search date was recorded to ensure process traceability.

Studies that mentioned AI only superficially, without presenting an application, analysis, model, technique, or methodological discussion related to civil engineering, were excluded. AI studies applied to fields outside the scope of the review, such as medicine, finance, education, agriculture, or industry in general, were also excluded when there was no direct relationship with construction, infrastructure, the built environment, or typical civil engineering problems. Duplicate studies, retracted records, or publications with editorial inconsistencies that compromised their scientific validity were also disregarded.

Studies without a clear description of the AI technique used, without presentation of results, without validation, without practical application, or without sufficient methodological discussion to support the proposed analysis were excluded. Stand-alone abstracts, editorials, letters to the editor, news items, opinion pieces, presentations without a full article, and materials without a scientific structure compatible with the review objectives were also excluded.

Regarding language, studies not written in Portuguese, English, or Spanish were excluded. Because no fixed time frame was adopted, no study was excluded by publication year; selection was guided by thematic relevance, open-access availability, and the study's capacity to contribute to the analysis of AI applications in civil engineering.

Secondary studies, such as literature reviews, systematic reviews, and bibliometric studies, were not automatically discarded. These records were separated from primary studies and used to support theoretical contextualization and comparative discussion, thereby avoiding overlap of secondary evidence in the main analysis of empirical applications.

Study selection was performed in successive stages. First, open-access availability was verified. Next, the titles of open-access records were assessed. Records classified as

"include" or "uncertain" proceeded to abstract review. After this stage, the final inclusion or exclusion decision was made.

The selected texts were read with particular attention to the methodology and results sections, when available, to confirm the nature of the study and identify information relevant to data extraction.

Screening began with 241 records identified in the initial search. Of this total, 147 were excluded because open access could not be confirmed, whereas 94 records were retained for title screening.

During title screening, 32 studies were classified as "include," 58 were excluded, and 4 remained uncertain. Thus, the 36 records classified as "include" or "uncertain" were forwarded for abstract review.

During abstract review, 35 studies were included and 1 was excluded for insufficient relevance to the scope of civil engineering. Subsequently, in the final verification, 1 retracted publication was excluded, resulting in 34 eligible studies. Of this set, 6 were classified as literature reviews and used to support theoretical contextualization and comparative discussion; they were not included in the main synthesis of primary studies. The remaining 28 studies proceeded to the methodological assessment, at which stage 1 study was subsequently excluded because it did not effectively apply AI in its method, resulting in 27 primary studies in the final corpus.

This set corresponds to the studies used to identify applications of AI in civil engineering, considering the techniques employed, application areas, data types, metrics, results, limitations, and research opportunities.

2.1. Data extraction

After defining the documentary corpus, the data from the included studies were analytically extracted. This stage was intended to organize the information required to compare the studies and construct the analytical dimensions.

When applicable, the extraction covered study identification, title, civil engineering area, problem investigated, study objective, AI technique used, data type, evaluation metrics, main results, and reported limitations.

In line with the concern for transparency recommended by PRISMA 2020 (Page et al., 2021), a specific instrument was adopted to assess the methodological quality of the included studies. This instrument was operational in nature and was developed to verify the minimum consistency of the studies regarding methodological clarity, validity of procedures, appropriateness of metrics, discussion of limitations, and reproducibility.

The assessment considered seven criteria: clarity of the objective, description of the database, justification of the AI technique used, model validation or comparison, appropriateness of the metrics employed, discussion of limitations, and reproducibility. Each criterion received a score from 0 to 2, where 0 indicated that the criterion was not met, 1 indicated that it was partially met, and 2 indicated that it was fully met.

The total score ranged from 0 to 14 points. For classification purposes, studies scoring from 0 to 5 were considered to have low methodological quality; those scoring from 6 to 10, medium quality; and those scoring from 11 to 14, high quality. For analytical purposes, the documentary corpus was organized by distinguishing primary and secondary studies. Primary studies correspond to works presenting applications, models, experiments, case studies, empirical evaluations, or computational proposals applied to civil engineering.

Secondary studies, such as literature reviews, systematic reviews, and bibliometric studies, were retained to support theoretical contextualization and comparative discussion of the findings. This distinction was adopted to avoid overlap of secondary evidence and preserve the main analysis of studies involving the direct application of AI.

Data analysis was organized by thematic dimensions to avoid a fragmented, article-by-article presentation. The dimensions considered include the areas of civil engineering covered, the AI techniques used, the purposes of the applications, the types of data employed, evaluation metrics, practical contributions, methodological limitations, and research gaps.

The synthesis of results was constructed in a narrative and analytical manner, relating the findings of the primary studies to the contextual support of secondary studies, when relevant.

3. RESULTS

3.1. Results of the methodological quality assessment

The methodological quality assessment indicated a predominance of studies classified as high quality. Of the 27 studies included in the final corpus, 23 were classified as having high methodological quality, corresponding to 85.2% of the corpus, whereas 4 studies were classified as medium quality, equivalent to 14.8%. No study was classified as having low methodological quality. This result indicates that most studies present sufficient methodological consistency to support the proposed analytical synthesis, although the studies classified as medium quality require more cautious interpretation regarding the validity, reproducibility, and generalizability of their findings.

The main strengths observed were clarity of objectives, appropriateness of AI techniques to the problems investigated, and the use of metrics compatible with regression, classification, optimization, detection, or monitoring tasks. A substantial proportion of the studies also presented validation through experimental databases, simulations, model comparisons, case studies, or performance analysis.

Despite this positive pattern, recurring methodological weaknesses were identified. The main limitations concern incomplete descriptions of databases, lack of openly available code or datasets, dependence on proprietary databases, validation restricted to specific contexts, and limited discussion of reproducibility. These aspects indicate that, although the corpus presents overall methodological consistency, study replication and the transfer of models to different civil engineering scenarios remain relevant challenges.

The assessment also made it possible to identify studies requiring more cautious reading, especially those with less technical detail, limited validation, or low reproducibility. These cases do not invalidate the analysis, but they call for a prudent interpretation of the reported results.

3.2. Application areas identified

The analytical extraction of the 28 studies showed that AI applications in civil engineering are distributed across different technical and managerial domains, confirming the breadth of the topic and its presence in prediction, monitoring, optimization, inspection, and decision-support problems. Because of the chapter's length limitation, the summary table of the 28 studies, containing the individual data used in the analysis, was made available in the review's supplementary repository.

In transportation and road infrastructure, the studies addressed problems such as adaptive congestion control in vehicular networks, identification of accident hotspots on highways, and interregional logistics optimization. In these applications, AI was used to handle dynamic flows, time series, multimodal data fusion, and decisions in environments with high operational variability (Deineko; Jungnickel; Kehrt, 2024; Jing et al., 2025; Zhu, 2025; Patra; Maharana, 2026).

In geotechnical, mining, and geological engineering, the studies focused on problems related to predicting stresses in mine pillars, landslide-dam stability, soil liquefaction, rock-image recognition, slope stability, and risks associated with complex geological conditions. These studies indicate that AI has been used to expand predictive capacity in contexts characterized by uncertainty, spatial heterogeneity, and limited observational data (Hoang; Pham, 2016; Gong et al., 2022; Li et al., 2025; Zvarivadza et al., 2025; Torres; Dungca, 2026).

The studies analyzed in the area of structures, bridges, and structural health monitoring applied AI models to predict seismic response, support digital twins, identify damage in reinforced-concrete beams, monitor deformations in columns, and optimize the performance of prefabricated bridges. These applications point to the growing use of AI to support structural analysis, predictive maintenance, and real-time monitoring of critical infrastructure (Jayasinghe et al., 2024; Akhlaq et al., 2025; Pasityothin et al., 2025; Ullegaddi et al., 2025; Yang; Han; Yang, 2025).

In hydraulic infrastructure, an application of artificial neural networks was identified to support the preliminary design of cyclopean concrete dams intended for water collection and storage. The study used geomorphological variables and digital elevation models to predict design parameters, such as the location of the axis and the length and height of the dam, demonstrating the use of AI to support standardization and efficiency in the preliminary sizing process (Lizarbe-Alarcón et al., 2025).

In construction materials and digital construction, the studies addressed prediction of the compressive strength of special concretes, fiber–matrix interface behavior in fiber-reinforced concrete, geometric inspection of 3D concrete printing, and performance prediction of asphalt modified with plastic waste. In these cases, AI appears as an alternative for reducing experimental effort, supporting material formulations, automating inspections, and providing faster predictive models for properties of engineering interest (Aslam et al., 2020; Cui et al., 2025; Putra; Rokade, 2025; Rana; Hossain; Li, 2025; Park; Bolander; Lim, 2026).

Applications in urban planning, urban hydrology, geotechnology, and environmental management were also identified. The studies covered urban ventilation corridors, parcel-level imperviousness estimation, identification and prediction of residents' demands in smart cities, automated building detection, simulation of ground-penetrating radar (GPR) data for metal pipes, and permeable pavements in smart cities. These results indicate that AI has contributed to spatial analyses, support for geographic information systems, data-driven urban planning, smart urban governance, and underground infrastructure monitoring (Techapinyawat et al., 2024; Benjamin; Dharmakkan, 2025; Guo et al., 2025; Khatua; Bhattachary; Aithal, 2025; Zhang et al., 2025; Chen et al., 2026).

Finally, construction management, facility maintenance, and the circular economy also emerged as relevant fields. Studies on BIM, AI, and sustainability, knowledge-based building maintenance, and construction-waste management using multicriteria methods show that AI has been employed not only in technical prediction problems but also to support managerial decision-making, resource optimization, and sustainability in the built environment (Ehab; Mahdi; El-Helloty, 2025; Weerakoon et al., 2025; Marović et al., 2026).

3.3. AI techniques used

The techniques identified in the studies reveal a methodologically diverse field. Among supervised models, Random Forest, XGBoost, Gradient Boosting, LightGBM, AdaBoost, NGBoost, support vector machines (SVMs), decision trees, regression, and ensemble-learning models are prominent. These techniques were applied mainly to prediction, classification, risk assessment, and performance-optimization problems (Singh et al., 2024; Akhlaq et al., 2025; Li et al., 2025; Lizarbe-Alarcón et al., 2025; Zvarivadza et al., 2025).

Artificial neural networks and deep-learning models were also recurrent. Applications involving artificial neural networks (ANNs), multilayer perceptrons (MLPs), convolutional neural networks (CNNs), You Only Look Once (YOLO), AlexNet, graph neural networks, attention-based models, generative networks, and architectures for image translation and style transfer were identified. These approaches were employed in computer vision, structural monitoring, image recognition, object detection, data generation, and structural-response analysis (Gong et al., 2022; Jayasinghe et al., 2024; Techapinyawat et al., 2024; Cui et al., 2025; Guo et al., 2025).

Hybrid models, optimization algorithms, and domain-knowledge-oriented methods were also identified. These include physics-informed models, physics-informed neural networks (PINNs), BIM-based methods, knowledge-based systems, fuzzy graphs, Rough Set Machine Learning, metaheuristics, Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), multiple-criteria decision-making (MCDM), and data-imputation strategies combined with machine learning. This diversity indicates that AI in civil engineering is not limited to the direct application of predictive algorithms but instead involves combinations of data, physical models, expert knowledge, and decision-support systems (Alavi; Mashayekhi; Zolfaghari, 2025; Benjamin; Dharmakkan, 2025; Weerakoon et al., 2025; Yang; Han; Yang, 2025; Torres; Dungca, 2026).

3.4. Data types and evaluation metrics

The types of data used were varied and reflect the heterogeneity of civil engineering problems. Geotechnical data, rock-sample statistics, sensor records, satellite and unmanned aerial vehicle (UAV) images, rock images, concrete-filament images, geospatial data, digital elevation models, maintenance records, questionnaires, finite-element simulations, nonlinear time-history analysis (NLTHA) simulations, GPR data, well logs, traffic time series, and experimental materials data were identified.

Evaluation metrics also varied according to the nature of the tasks. In regression problems, metrics such as MSE, MAE, RMSE, MAPE, R^2, and correlation were used. In

classification, detection, and segmentation tasks, accuracy, precision, recall, F1-score, confusion matrix, AUC, sensitivity, specificity, mean average precision (mAP), and structural-similarity measures appeared. In optimization and decision studies, metrics such as rankings, repair costs, seismic damage, sensitivity analysis, optimization efficiency, and operational performance indicators were employed.

This variety of data and metrics shows that the evaluation of AI in civil engineering must be interpreted according to the purpose of the study. Models aimed at predicting mechanical properties, for example, require metrics different from those used in object detection, risk classification, logistics optimization, or multicriteria decision support. Direct comparison among studies must therefore be undertaken cautiously, considering the type of problem, dataset, application scale, and performance criterion adopted.

3.5. Main contributions identified

The results extracted from the studies indicate that AI contributes mainly to expanding predictive capacity, reducing analysis time, automating tasks, supporting decisions, and optimizing resources. In construction materials, neural networks and gene-expression programming models were used to predict compressive strength and reduce dependence on extensive laboratory testing (Aslam et al., 2020; Rana; Hossain; Li, 2025). In geotechnical engineering and mining, ensemble-learning models and interpretable methods contributed to risk assessment, stress prediction, and decision support in contexts of high technical uncertainty (Li et al., 2025; Zvarivadza et al., 2025; Torres; Dungca, 2026).

The studies analyzed in the area of structures and infrastructure indicate that AI models can function as faster alternatives to complex simulations, support digital twins, and assist with damage monitoring. Models such as XGBoost, ANN, MLP, and PINN were associated with predicting seismic responses, structural monitoring, reducing computational costs, and improving decision-making for bridges, ports, and reinforced-concrete elements (Jayasinghe et al., 2024; Akhlaq et al., 2025; Lizarbe-Alarcón et al., 2025; Ullegaddi et al., 2025; Yang; Han; Yang, 2025).

In urban planning, transportation, and geotechnology, the studies show that AI can support spatial analysis, identification of critical areas, data fusion, and modeling of urban systems. The application of graph neural networks, multimodal fusion models, reinforcement learning, and computer vision demonstrates the potential of these techniques to address dynamic urban phenomena such as imperviousness, congestion, accidents, ventilation, and subsurface data (Techapinyawat et al., 2024; Guo et al., 2025; Jing et al., 2025; Chen et al., 2026; Patra; Maharana, 2026).

AI also contributes to sustainability, management, and the circular economy. The studies analyzed show applications in sustainable construction planning, building maintenance, waste optimization, permeable pavements, and waste-modified materials. These results reinforce the relationship between AI and support for more efficient, sustainable, and data-driven practices in the construction industry (Benjamin; Dharmakkan, 2025; Ehab; Mahdi; El-Helloty, 2025; Putra; Rokade, 2025; Weerakoon et al., 2025; Marović et al., 2026).

3.6. Recurring limitations

The limitations reported in the studies are concentrated in four main dimensions. The first concerns data quality, availability, and representativeness. Some studies depend on small databases, proprietary data, sensitive information, specific operational records, simulations, or datasets restricted to a particular location, which limits the generalization of the models to other civil engineering contexts (Gong et al., 2022; Alavi; Mashayekhi; Zolfaghari, 2025; Zvarivadza et al., 2025).

The second dimension involves validation and reproducibility. Some studies presented validation restricted to the case study itself, failed to make code available, provided only partial descriptions of computational parameters, or depended on specific experimental conditions. These aspects hinder independent replication and the transfer of models to broader professional or institutional applications.

The third dimension concerns interpretability. High-performance models, especially deep neural networks and complex architectures, may operate as systems that are difficult to explain, which reduces their acceptance in engineering decisions requiring traceability, transparency, and technical responsibility (Putra; Rokade, 2025; Sun et al., 2026; Torres; Dungca, 2026).

The fourth dimension is associated with scalability and computational cost. Some applications depend on extensive simulations, large volumes of data, complex training, or intensive processing of images and time series.

4. DISCUSSION OF RESULTS

4.1. AI as a cross-cutting dimension in civil engineering

The results indicate that AI has moved beyond a peripheral position in civil engineering and has become a cross-cutting dimension of investigation and application. Evidence extracted from the studies analyzed shows that AI is present in traditionally dis-

tinct areas, such as structures, geotechnical engineering, construction materials, transportation, urban planning, building maintenance, hydraulic infrastructure, geotechnology, waste management, and structural health monitoring. This breadth suggests that AI should be interpreted not merely as a computational tool but as a set of approaches capable of changing modes of prediction, analysis, decision-making, and control in different civil engineering problems.

This cross-cutting nature is consistent with the literature on Construction 4.0, in which technologies such as BIM, digital twins, computer vision, sensors, the Internet of Things, and machine learning operate in an integrated manner throughout the life cycle of buildings and infrastructure (Baduge et al., 2022). In the studies analyzed, this integration appears both in applications aimed at design and structural analysis and in solutions for operation, maintenance, inspection, logistics, and sustainability. AI therefore emerges as a linking element among data, models, processes, and decisions.

However, the diversity of applications also reveals a field that remains fragmented. The studies analyzed tend to focus on specific problems, with databases, metrics, and models particular to each domain. This fragmentation hinders the construction of a systemic view of the use of AI in civil engineering and reinforces the need for reviews that organize applications by area, technique, data type, purpose, and limitation. This finding is consistent with discussions pointing to the difficulty of integrating intelligent solutions into broader infrastructure-management, design, execution, and operation workflows (Deineko; Jungnickel; Kehrt, 2024; Mishra et al., 2024).

4.2. Predominance of predictive models and advancement of hybrid approaches

The analysis of the studies reveals a predominance of models focused on prediction, classification, detection, and optimization. In construction materials, for example, machine-learning models and neural networks were used to estimate mechanical properties, such as the compressive strength of special concretes, with the aim of reducing dependence on extensive experimental testing and accelerating formulation and performance-assessment processes (Aslam et al., 2020; Rana; Hossain; Li, 2025). In geotechnical engineering and mining, ensemble-learning models, data imputation, and interpretable methods were applied to predicting stresses in pillars, landslide-dam stability, and soil liquefaction (Li et al., 2025; Zvarivadza et al., 2025; Torres; Dungca, 2026).

In structural studies, predictive models appear as an alternative or complement to traditional numerical methods with high computational cost. The application of XGBoost, artificial neural networks, surrogate models, PINN, and MLP to bridges, port structures,

and reinforced-concrete beams demonstrates that AI can reduce processing time, support simulations, identify damage, and expand monitoring capacity (Jayasinghe et al., 2024; Akhlaq et al., 2025; Ullegaddi et al., 2025; Yang; Han; Yang, 2025). This movement does not eliminate classical engineering methods but suggests a trend toward complementarity among physical modeling, computational simulation, and data-driven learning.

A relevant point is the growth of hybrid approaches. The studies are not limited to the direct application of AI algorithms; in many cases, they combine machine-learning models with BIM, geographic information systems (GIS), multicriteria methods, digital twins, finite-element simulations, physical knowledge, or optimization techniques. This trend is important because civil engineering problems are rarely purely statistical. They involve regulatory constraints, physical laws, environmental variability, material uncertainties, and multicriteria decisions. In this regard, approaches such as PINN, PIML, BIM-integrated models, GIS with metaheuristics, and multicriteria decision-making methods indicate a promising direction for applications that are more robust and aligned with the technical domain of engineering (Alavi; Mashayekhi; Zolfaghari, 2025; Weerakoon et al., 2025; Yang; Han; Yang, 2025; Sun et al., 2026).

4.3. Data, validation, and reproducibility as central challenges

Although most studies presented high methodological quality, the analysis showed that the consolidation of AI in civil engineering depends heavily on data quality, robust validation, and the reproducibility of procedures. Many studies achieve good performance on specific datasets, but depend on limited experimental data, simulations, proprietary information, local records, or particular application conditions. This characteristic limits model generalization and requires caution when transferring results to other contexts.

This problem is particularly sensitive in geotechnical engineering, infrastructure, and structural monitoring, areas in which data are influenced by local conditions, spatial variability, material properties, loading history, exposure environment, and operational uncertainties. Studies on landslide-dam stability, soil liquefaction, stresses in pillars, and the seismic response of bridges illustrate how model performance depends on the representativeness of datasets and the quality of input variables (Akhlaq et al., 2025; Li et al., 2025; Zvarivadza et al., 2025; Torres; Dungca, 2026).

Validation emerges as another critical point. In some studies, assessment is performed through simulations, cross-validation, or model comparison, which contributes to the internal robustness of the results. External validation under real field conditions or using independent datasets, however, remains a challenge. This aspect is relevant because models with high performance in controlled environments may perform less well when applied to

actual construction projects, different regions, new materials, or operational situations not represented in the training set.

Reproducibility poses a further obstacle. The lack of open data, code, hyperparameters, preprocessing routines, or implementation details makes it difficult to replicate studies and compare models. Although some studies present interfaces, detailed simulations, or robust metrics, the scientific consolidation of the field requires greater transparency in making data and procedures available. This point is essential for AI models to advance from demonstrative applications to tools that can be effectively incorporated into professional practice.

4.4. Interpretability, technical confidence, and professional responsibility

The discussion of interpretability is central to the adoption of AI in civil engineering. In areas such as structures, geotechnical engineering, road safety, urban planning, and critical infrastructure, decisions have technical, economic, environmental, and human implications. It is therefore not sufficient for a model to present high predictive performance; its results must be understandable, auditable, and technically justifiable.

The studies analyzed show a recurring tension between performance and explainability. Models based on deep neural networks, complex architectures, generative models, or ensembles may achieve high accuracy but frequently operate with limited transparency. This characteristic hinders their acceptance in regulated contexts or in decisions that require formal technical responsibility. Conversely, interpretable approaches, such as rule-based models, Rough Set Machine Learning, SHapley Additive exPlanations (SHAP), sensitivity analysis, and physics-informed hybrid models, offer ways to bring computational performance and technical reliability closer together (Akhlaq et al., 2025; Chen et al., 2026; Sun et al., 2026; Torres; Dungca, 2026).

Interpretability is also related to communication between AI specialists and civil engineering professionals. Models that are difficult to explain tend to limit practical use when engineers, managers, and decision-makers cannot understand the factors influencing a prediction. Thus, studies presenting interfaces, explainable rules, variable-importance analysis, or integration with physical models help reduce the distance between computational research and professional application.

This is especially critical because civil engineering operates under principles of safety, traceability, and accountability. The incorporation of AI must respect these principles, preventing models from being used as autonomous black boxes in critical decisions. The most promising trend appears to be the use of AI as a decision-support system rather

than as a complete replacement for technical judgment. Thus, the value of AI lies in expanding the engineer's analytical capacity, not in displacing professional responsibility.

This responsibility extends, with equal rigor, to ethics in academic research in engineering and science. To safeguard methodological and authorship integrity, the recently established Policy on Integrity in Scientific Activity of the National Council for Scientific and Technological Development (CNPq), Ordinance No. 2,664/2026, sets forth explicit guidelines for the responsible use of generative artificial intelligence (GenAI). The policy requires researchers to formally declare the use of GenAI tools at any stage of scientific research—whether in conception, writing, data analysis, or submission—specifying the tool and its purpose (CNPq, 2026).

In accordance with the principle that technology should not operate autonomously and without restriction, CNPq strictly prohibits the submission of content generated by GenAI as though it were of human authorship and holds authors fully responsible for any plagiarism or inaccuracies. In addition, to ensure confidentiality and ethical integrity in scientific evaluations, the policy also prohibits entering third-party projects into these platforms for the preparation of review reports. These rules strengthen the premise that AI is an enabler of knowledge and civil engineering practice, requiring nonnegotiable human governance and responsibility throughout its development and application stages (CNPq, 2026).

4.5. Contributions to sustainability, safety, and decision-making

The results also show that AI can contribute to broader civil engineering objectives, especially sustainability, safety, and data-driven decision-making. In materials and pavements, intelligent models were applied to predict the performance of concrete, modified asphalt, and permeable systems, helping reduce testing, optimize mixtures, evaluate alternatives, and support practices related to the circular economy (Aslam et al., 2020; Benjamin; Dharmakkan, 2025; Putra; Rokade, 2025; Rana; Hossain; Li, 2025).

In construction and maintenance management, the integration of AI, BIM, and knowledge-based systems appears as an alternative for improving planning, cost control, resource allocation, and asset maintenance. These studies indicate that AI can support the transition from reactive management to more predictive and planned management, especially when integrated with operational data, digital models, and performance indicators (Ehab; Mahdi; El-Helloty, 2025; Marović et al., 2026).

In safety and critical infrastructure, applications in tunnels, highways, bridges, ports, dams, and pipelines show that AI can assist in identifying risks, locating damage, predicting structural responses, and supporting preventive decisions. This potential is particularly

relevant in contexts where failures may cause significant human, economic, and environmental losses (Jayasinghe et al., 2024; Singh et al., 2024; Alavi; Mashayekhi; Zolfaghari, 2025; Jing et al., 2025). In urban planning, the analysis of residents' demands through large language models (LLMs), BERTopic, and the combination of variational mode decomposition (VMD) and SVM, termed VMD-SVM, extends the use of AI as support for smart urban governance and citizen-centered decision-making (Zhang et al., 2025).

However, AI's contribution to sustainability and safety depends on its integration with institutional processes, reliable data, and appropriate validation. Isolated models, even when technically promising, have limited impact if they are not incorporated into actual design, operation, maintenance, and management workflows. The practical contribution of AI should therefore be assessed not only by algorithmic performance but also by its capacity to produce better, more transparent, sustainable, and professionally applicable decisions.

4.6. Research gaps and opportunities

The analysis of the studies makes it possible to identify relevant gaps for future research. The first concerns the need for open, standardized, and representative datasets. The absence of shareable data limits comparisons among models, study replication, and the construction of civil engineering benchmarks. This point is especially important in areas such as geotechnical engineering, structures, infrastructure monitoring, and urban planning, in which data strongly depend on local context and specific operational conditions.

The second gap involves the external and multicenter validation of models. Many studies demonstrate good performance on their own datasets, in simulations, or in isolated case studies, but there is still a need to test models in different regions, materials, construction projects, environmental conditions, and institutional contexts. Future research should advance the development of validation protocols that make it possible to assess robustness, transferability, and generalization.

The third opportunity lies in integrating AI, BIM, GIS, digital twins, and sensors. The studies analyzed indicate that more robust solutions tend to emerge when AI is incorporated into digital ecosystems rather than used as an isolated technique. This integration may foster applications in predictive maintenance, real-time monitoring, urban planning, asset management, scenario simulation, and multicriteria decision-making (Baduge et al., 2022; Jayasinghe et al., 2024; Techapinyawat et al., 2024; Marović et al., 2026).

The fourth gap concerns model explainability and governance. The literature analyzed shows that AI models need to be interpretable, auditable, and compatible with the technical responsibility required in civil engineering. There is therefore room for research

that combines high performance with transparency, using explainable-AI methods, physics-informed models, sensitivity analysis, interpretable rules, and decision-support interfaces.

Finally, there is an opportunity for studies that bring academic production closer to professional practice. This involves validating models in the field, engaging public- and private-sector stakeholders, building tools usable by engineers, assessing the cost-effectiveness of implementation, and studying organizational barriers to AI adoption. The consolidation of AI in civil engineering will depend less on the mere availability of algorithms and more on the capacity to integrate them with real problems, reliable data, decision-making processes, and technical responsibilities.

4.7. Synthesis of the answers to the research questions

The answers to the research questions were derived from the integrated analysis of the 27 primary studies included in the main synthesis. With regard to RQ1, the results point to the use of diverse AI techniques, including supervised machine learning, artificial neural networks, deep learning, ensemble models, computer vision, optimization algorithms, multicriteria methods, graph neural networks, and physics-informed approaches (Techapinyawat et al., 2024; Akhlaq et al., 2025; Cui et al., 2025; Weerakoon et al., 2025; Yang; Han; Yang, 2025; Zvarivadza et al., 2025; Sun et al., 2026). With regard to RQ2, the applications confirm the presence of AI in areas such as structures, geotechnical engineering, materials, transportation, urban planning, construction management, maintenance, sustainability, geotechnology, and structural health monitoring (Jayasinghe et al., 2024; Rana; Hossain; Li, 2025; Zhang et al., 2025; Zvarivadza et al., 2025; Chen et al., 2026; Marović et al., 2026; Patra; Maharana, 2026).

Regarding RQ3, the practical contributions are concentrated in expanding predictive capacity, reducing computational time, automating inspections, optimizing resources, supporting predictive maintenance, assessing risks, and improving decision-making (Aslam et al., 2020; Jayasinghe et al., 2024; Singh et al., 2024; Akhlaq et al., 2025; Cui et al., 2025; Ehab; Mahdi; El-Helloty, 2025). Regarding RQ4, recurring challenges involve data quality and availability, open access to datasets and code, external validation, generalization, and interpretability (Gong et al., 2022; Alavi; Mashayekhi; Zolfaghari, 2025; Li et al., 2025; Putra; Rokade, 2025; Sun et al., 2026; Torres; Dungca, 2026). Finally, RQ5 points to opportunities associated with the creation of open datasets, multicenter validation, integration among AI, BIM, GIS, sensors, and digital twins, explainable models, and a closer relationship between academic research and professional application (Baduge et al., 2022;

Jayasinghe et al., 2024; Techapinyawat et al., 2024; Yang; Han; Yang, 2025; Marović et al., 2026; Sun et al., 2026; Torres; Dungca, 2026).

Relating the answers to the specific research questions, grounded in the selected primary studies and the analyses developed in the preceding sections, makes it possible to formulate an answer to the main research question. A reading of the corpus suggests that AI has been applied across civil engineering, using supervised techniques, neural networks, deep learning, ensemble models, computer vision, optimization, and physics-informed approaches in areas such as structures, geotechnical engineering, materials, transportation, urban planning, infrastructure, maintenance, sustainability, and structural health monitoring. The observed contributions are concentrated in predictive capacity, automation, decision support, resource optimization, and risk mitigation, subject to overcoming limitations concerning data quality, external validation, reproducibility, and interpretability. The identified opportunities point to open datasets, multicenter validation, integration among AI, BIM, GIS, sensors, and digital twins, explainable models, and a closer relationship between research and professional practice. Taken together, this evidence characterizes a field undergoing consolidation, whose maturation appears to depend less on the availability of algorithms than on the integration of data, models, technical-domain knowledge, and decision-making processes.

5. FINAL CONSIDERATIONS

This exploratory systematic review analyzed the main applications of AI in civil engineering, considering the techniques used, application areas, practical contributions, methodological limitations, and research opportunities. Through the procedures for searching, screening, selecting, and analyzing the studies, it was possible to organize an initial overview of the incorporation of AI into problems of prediction, risk classification, optimization, automation, monitoring, and decision support.

The results indicate that AI has been consolidating its position as a cross-cutting approach in civil engineering, with applications in structures, geotechnical engineering, construction materials, transportation, urban planning, infrastructure, maintenance, construction management, sustainability, and structural health monitoring. The contributions identified involve improved predictive accuracy, reduced computational time, automated inspections, support for predictive maintenance, resource optimization, risk assessment, and improved technical decisions.

However, the consolidation of these applications depends on overcoming recurring limitations, such as data quality and availability, limited openness of datasets and code,

insufficient external validation, difficulty of generalization, and limited interpretability of complex models. These aspects demonstrate that the advancement of AI in civil engineering depends not only on algorithmic performance but also on methodological transparency, reproducibility, alignment with the technical domain, and integration with professional practices.

As a limitation of the review itself, its restriction to the Scopus database and the requirement for open access to the full text should be highlighted. Although these decisions ensured traceability and the feasibility of reading the studies in full, they may also have restricted the scope of the corpus analyzed. Adopting open access as an operational criterion constitutes a potential risk of selection bias and should be considered when interpreting the results. For this reason, the results should be interpreted as an initial, systematized overview rather than as an exhaustive representation of scientific production on AI in civil engineering.

Despite this limitation, the review contributes by organizing the application areas, techniques employed, data types, metrics, benefits, limitations, and gaps identified in the studies analyzed. This systematization also has an educational function, as it supports the definition of research topics and improves academic supervision within the Graduate Program in Civil Engineering.

As a way forward, it is recommended that future searches be expanded to multiple databases, that analyses by civil engineering subfield be deepened, that research involving open datasets and external validation be encouraged, and that tools applicable to professional practice be developed. It is also relevant to advance the integration of data-driven models, physical knowledge, and mechanisms that facilitate the interpretation of results. In this way, AI can advance from isolated applications to solutions that are more robust, transparent, and integrated with the technical, environmental, and social challenges of contemporary civil engineering. The incorporation of these technologies into civil engineering should therefore occur in conjunction with technical judgment and professional responsibility.

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PART II

Materials, waste, and performance

CHAPTER 4

Mechanical characterization and applications of fiber-reinforced concrete: contributions to engineering practice

Ramoel Serafini, Stefany dos Anjos Coronel, Alicia Martinez Batista, Gabriele Silva Costa de Almeida, Felipe Augusto da Silva Barbosa, Albert de la Fuente Antequera

1. INTRODUCTION

Over recent decades, fiber-reinforced concrete (FRC) has established itself as a structural material capable of partially or fully replacing conventional reinforcement in a wide range of infrastructure applications (Plizzari; Tiberti, 2006; Caratelli et al., 2011; de la Fuente et al., 2012; Carpio et al., 2019; Krahl et al., 2021; Salvador et al., 2024). The transition from plain concrete to FRC represents a fundamental shift in the structural design paradigm: the transformation of a brittle material into a composite with pseudo-ductile behavior, characterized by its ability to maintain structural integrity and redistribute stresses after cracking of the cementitious matrix. This evolution has been driven by international regulatory milestones, such as the fib Model Code (fib, 2024), and national ones, such as ABNT NBR 16935 (ABNT, 2021a), which establishes guidelines for the design of fiber-reinforced concrete structures, complemented by the testing standards ABNT NBR 16939 (ABNT, 2021b) and ABNT NBR 16940 (ABNT, 2021c) for the mechanical characterization of the material.

One of the main barriers to the widespread adoption of FRC lies in the characterization of post-cracking parameters, which is typically performed through the mechanical tests illustrated in Figure 1. In this context, the study and simplification of the double-edge wedge splitting (DEWS) test emerge as an important technological advancement. By inducing a predominantly Mode I fracture in smaller cubic specimens,

the DEWS test facilitates the derivation of constitutive equations and design parameters for both the serviceability limit state (SLS) and the ultimate limit state (ULS). The proposed elimination of expensive displacement measurement devices (clip gauges) through geometric correlations between piston displacement and crack opening displacement (COD) simplifies quality control procedures, enabling laboratories with limited infrastructure to perform material validation.

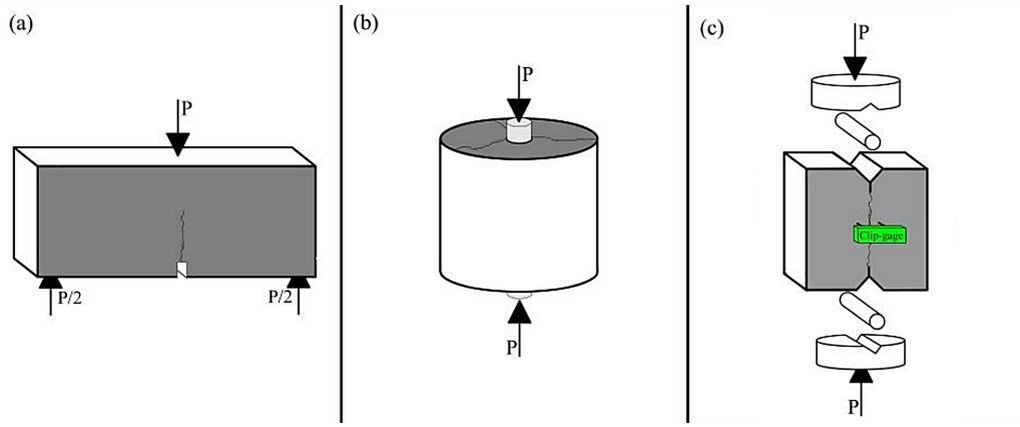


Figure 1 – Mechanical characterization tests for steel fiber-reinforced concrete (SFRC): (a) three-point bending test, (b) double punch test, and (c) conventional DEWS test.

Source: Adapted from Coronel, 2024.

Beyond mechanical characterization and quality control, efficiency in concrete production is essential for the advancement of engineering, from both economic and technical perspectives. In this regard, it is well established that the mechanical performance of FRC is governed primarily by the interfacial transition zone (ITZ) between the fiber and the cementitious matrix (Cunha; Barros; Sena-Cruz, 2010; Abu-Lebdeh et al., 2011; Serafini et al., 2021a; Mineiro et al., 2022; Maia et al., 2025). Recent studies have introduced the surface treatment of steel fibers with nanosilica ($nSiO_2$) and chelating agents such as ethylenediaminetetraacetic acid (EDTA), aiming to increase microscopic surface roughness and promote pozzolanic reactions at the fiber–matrix interface (Rambo et al., 2021; Oh et al., 2021; Ren et al., 2022). This technological innovation makes it possible to reduce the amount of steel fibers used per cubic meter of concrete without compromising the toughness and post-cracking performance of the composite system.

This chapter synthesizes the scientific and technological contributions developed at Universidade São Judas Tadeu that have an impact on contemporary professional practice. The bridge between academic research and Brazilian industrial application involves

two fronts: the simplification of testing methods and interfacial nanotechnology. The objective is to provide engineers with tools to optimize processes and improve the efficiency of SFRC structures in an economically viable and socially responsible manner, contributing to the resilience of the urban and industrial infrastructure required for both national and international development.

2. ADVANCES IN THE DEWS TEST: PROPOSALS FOR STANDARDIZATION AND EFFICIENCY

Accurate determination of the post-cracking mechanical properties of SFRC, usually performed through bending tests on prisms, constitutes a fundamental pillar for the design of resilient and safe structures, as it quantifies the transition from the brittle behavior of the cementitious matrix to a pseudo-ductile response (Serafini et al., 2018; Figueiredo; Monte; Bitencourt Jr., 2022). However, the systematic implementation of this test faces logistical and economic barriers: the prisms are large (150 × 150 × 550 mm) and crack opening control requires high-precision extensometers. Together, these factors make the test impractical for routine quality control on construction sites and in small- to medium-sized laboratories (Monte et al., 2023).

Seeking faster and more practical alternatives for industrial applications, the Brazilian construction sector adopted the double punch test (DPT), widely known as the Barcelona test and standardized by ABNT NBR 16939 (ABNT, 2021b). This method represents a significant technological advancement by substantially simplifying specimen preparation and casting procedures, employing reduced-size cylindrical specimens (Ø100 × 100 mm or Ø150 × 150 mm), which facilitate handling, core extraction from existing structures, and routine quality control (Pujadas et al., 2013). However, despite its standardization and operational simplicity, the full acceptance of the DPT by the Brazilian market still faces significant resistance due to limitations associated with its complex fracture mechanism and the reliability of the parameters derived for quality control and structural design at both the serviceability and ultimate limit states (Coronel, 2024).

The main technical drawback of the DPT lies in the complexity of its failure mechanism, which differs substantially from the simpler fracture observed in a beam under bending or in a direct tensile test. Punching induces a radial tensile failure that generates a variable number of fracture planes (typically between one and five, depending on the fiber content), making the mechanical behavior of the material dependent on a complex three-dimensional stress state and on the internal friction coefficient of the matrix (Nogueira et al., 2021). Furthermore, the frictional interaction between the punching cylinder and the cementitious matrix may lead to unreliable responses in concretes that

have undergone chemical or physical deterioration, as is the case for concretes exposed to elevated temperatures (Rambo et al., 2018). This multiplicity of influencing factors hinders the establishment of an appropriate constitutive equation, thereby creating uncertainties for designers when converting experimental results into structural design parameters for fiber-reinforced concrete.

In addition to the mechanical issues, the DPT faces statistical challenges associated with its high variability and result dispersion, which directly affect the costs of quality control (Molins; Aguado; Saludes, 2009; Choumanidis et al., 2017; Rambo et al., 2018; Simão et al., 2019). For low fiber contents, commonly used in pavements and secondary linings, the technical literature indicates that more than 15 specimens may be required to ensure the statistical representativeness of the sample (Estrada Cáceres; Pialarissi Cavalaro; Figueiredo, 2021). This reduces the cost savings associated with the geometric simplicity of the specimen and increases the overall operational cost for the industry.

The instability observed in the post-peak stage—which is characteristic of concretes with low fiber contents—also compromises the accuracy of the DPT in characterizing the service behavior of SFRC (Simão et al., 2019). The complexity of the stress state generated by punching makes it difficult to accurately capture the transition between cracking of the cementitious matrix and the effective activation of fibers as a reinforcing mechanism. Instabilities frequently occur, masking the mechanical response at small crack openings and impairing the determination of the SLS, a critical parameter for crack control and durability assessment in structures such as segmental tunnel linings and industrial pavements. This "shadowing" effect in the early post-cracking results prevents designers from optimizing fiber dosage, often leading to overdesign due to the lack of reliable SLS-related data.

Given this gap between the normative complexity of the three-point bending test (3PBT) and the technical uncertainties associated with the DPT, the DEWS test emerges as a potentially valuable technological innovation for professional practice (di Prisco; Ferrara; Lamperti, 2013). By inducing a predominantly Mode I fracture, the DEWS test provides a cleaner mechanical response that more closely resembles direct tension, eliminating much of the undesirable friction and crushing effects present in the DPT and other indirect testing methods. This configuration facilitates the direct extraction of quality-control parameters, providing engineers with more robust data and lower statistical dispersion. Although the DEWS test represents an advancement in the identification of Mode I behavior compared with other indirect testing methods, its practical application in civil engineering faces significant challenges that limit its widespread adoption for routine quality control (Borges et al., 2019).

One of the main drawbacks of the conventional DEWS test lies in the extreme complexity of specimen preparation (di Prisco; Ferrara; Lamperti, 2013). In the conventional method, the specimens are not cast directly in their final geometry; instead, large prisms measuring 150 × 150 × 550 mm must be cast in accordance with the recommendations of ABNT NBR 5738 (ABNT, 2015) or ABNT NBR 16940 (ABNT, 2021c), and subsequently cut into cubes with 150 mm sides (Agra; Serafini; Figueiredo, 2021a, 2021b; Serafini et al., 2021b). After this stage, the 45° inclined wedges and the central notches must be produced manually with bench saws, as illustrated in Figure 2. This process is labor-intensive and time-consuming, making the test impractical for routine quality control on civil engineering projects, particularly given the large number of specimens typically required.

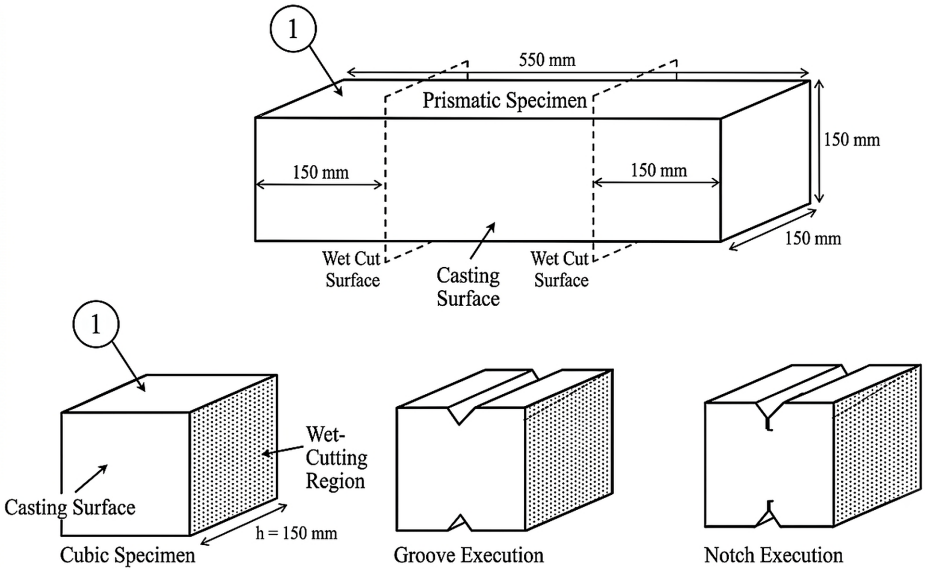


Figure 2 – Specimen preparation procedure using the conventional DEWS method.

Source: Adapted from Coronel et al., 2025.

In addition to the logistical burden, the manual fabrication of the specimen geometry introduces susceptibility to dimensional inaccuracies. Small deviations in wedge inclination or notch depth may increase result variability and statistical dispersion, thereby compromising the reliability of the extracted post-cracking parameters. Another economic and technical limitation is the requirement for sophisticated instrumentation. The conventional DEWS test relies on high-precision extensometers (clip gauges) attached to the sides of the specimen to monitor COD (di Prisco; Ferrara; Lamperti, 2013). The dependence on

these expensive and sensitive sensors, combined with the need for complex data acquisition systems, restricts the test primarily to advanced research laboratories, making its implementation impractical in field laboratories with limited infrastructure.

In this context, the contribution to contemporary professional practice arises from the simplification of the DEWS method, aimed at enabling its use for quality control and future standardization. This innovation is based on the use of molds with preformed grooves and the replacement of costly extensometers with a geometric correlation based on the testing machine's piston displacement, thereby facilitating access to testing procedures for determining the tensile properties of SFRC.

2.1. Advances in the simplification of the DEWS test

Regarding the technical aspects of specimen preparation, replacing prism cutting with direct casting of cubes with preformed grooves introduces changes in the internal fiber distribution due to the so-called "wall effect" (Monte et al., 2023). The experimental results available in the literature indicate that this alteration leads to a significant increase in post-cracking tensile strength for fiber contents of 40 kg/m³ and 60 kg/m³, both at small and at large crack openings (Monte et al., 2023; Coronel et al., 2025). In contrast, for lower fiber contents of 20 kg/m³, the influence of the preparation method proved to be statistically insignificant, suggesting that the impact of mold confinement is proportional to the volume fraction of fibers in the matrix (Coronel et al., 2025).

The adoption of these casting simplifications requires adjustment coefficients that align the mechanical responses obtained from the simplified DEWS test with those from the conventional method. The first parameter, the molding factor (K_m), is defined as the ratio between the post-cracking strength of directly cast specimens and that of specimens extracted from prisms, aiming to compensate for the increase in strength, particularly due to the "wall effect." Statistical analyses of literature data indicate an average estimate of 1.4 for K_m. Specifically regarding the use of the simplified DEWS method for determining design strengths, further studies are needed to expand the sample space, evaluate the dispersion and statistical distribution of K_m, verify its representativeness, and ensure the reliability of the post-cracking parameters obtained. To date, therefore, the advances related to the simplified DEWS method concerning the K_m factor are limited to demonstrating the magnitude of the influence of the casting procedure on post-cracking properties. Figure 3 summarizes the K_m values obtained in studies available in the literature (Monte et al., 2023; Coronel, 2024; Coronel et al., 2025).

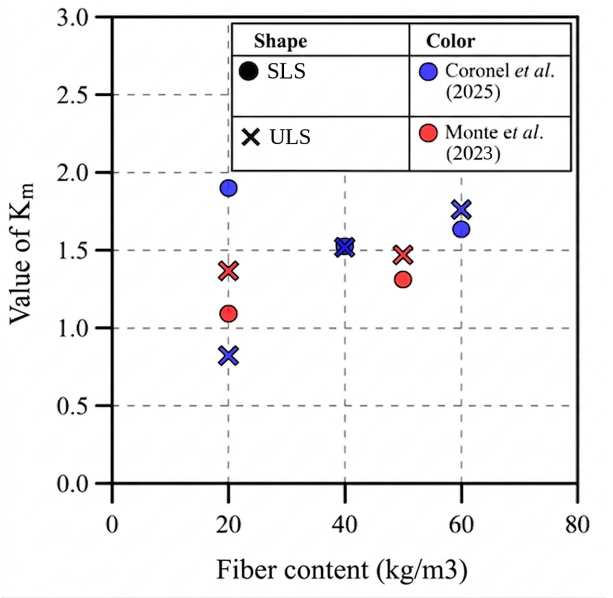


Figure 3 – K_m values obtained in the literature, by study and by property (SLS or ULS).

Source: Adapted from Coronel et al., 2025.

The replacement of the lateral clip gauges with control via piston displacement (machine stroke, or crosshead displacement) was first proposed by researchers at the University of São Paulo. The theoretical correlation between the COD and the piston displacement (D), based on the rigid-body motion hypothesis of the specimen, is given by Equation 1 (Monte et al., 2023):

$$COD = D - \delta_p \quad (1)$$

where

- COD is the crack opening displacement, expressed in millimeters;
- D is the piston displacement (stroke) corresponding to the COD at a given time, expressed in millimeters; and
- δ_p is the mean experimental piston displacement at the moment of concrete cracking, expressed in millimeters.

The proposed correlation was subsequently validated by researchers at Universidade São Judas Tadeu and proved consistent, as briefly discussed in this section on the basis of the results of Coronel et al. (2025). In this context, the displacement factor (K_d) addresses the simplification of the measurement system, replacing the direct control of the COD via lateral clip gauges with control via piston stroke displacement. The validation results

demonstrated that the accuracy of the prediction model is adequate for the characterization of large crack openings (COD = 1.25 mm), where errors ranged between 1.2% and 3.9%. However, the reliability of this simplification proved sensitive to the post-peak stability of the material; at contents of 20 kg/m³, the higher incidence of post-cracking instability resulted in poorer agreement with the prediction curve in the early stages, showing that control via piston stroke is more effective when the composite's ductility mitigates post-peak instability phenomena (Figure 4). The proposed K_d values of 1.05 (mean) and 1.1 (conservative) indicate low variation between the simplified and conventional DEWS methods. This coefficient adjusts for the minor inaccuracies inherent in the theoretical geometric correlation.

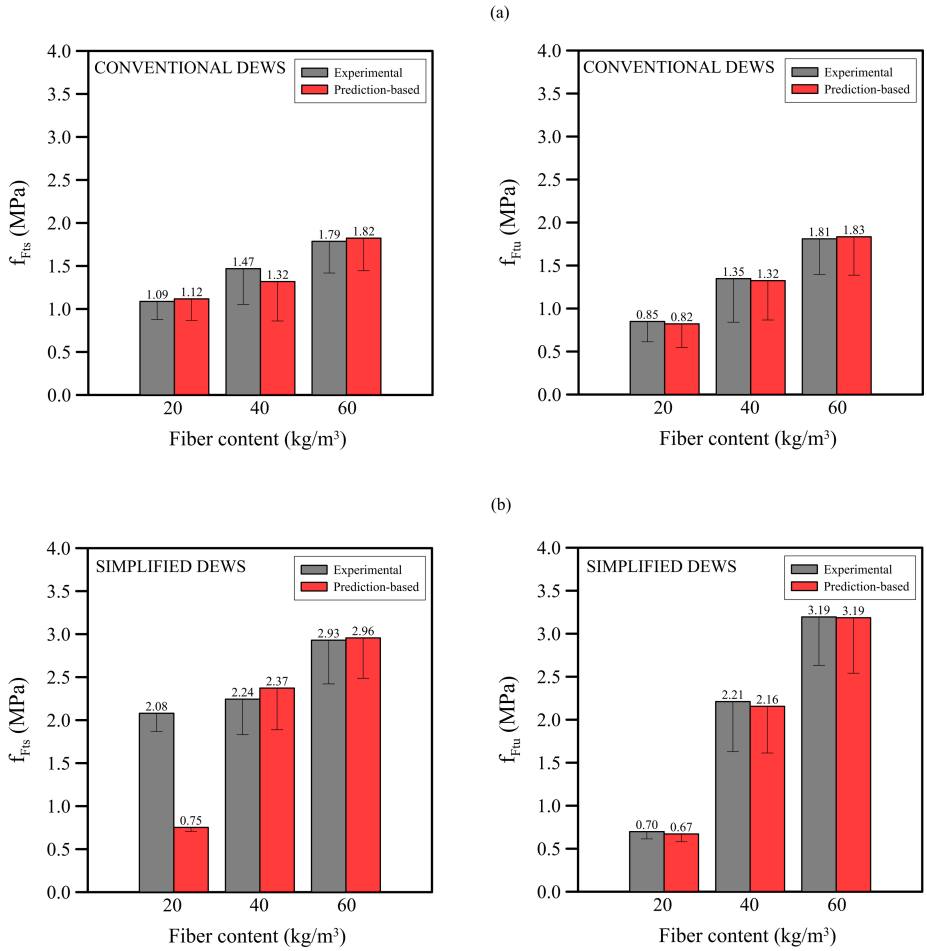


Figure 4 – Post-cracking results related to SLS (f_{Fts}) and ULS (f_{Ftu}) for (a) conventional DEWS and (b) simplified DEWS as a function of the displacement control model.

Source: Adapted from Coronel et al., 2025.

Thus, overcoming the limitations of the 3PBT and DPT through methods such as the simplified DEWS aligns Brazilian civil engineering with the goals of reducing operational costs and simplifying experimental procedures. This initiative promotes technological innovation and enables small industries to raise the quality standards of their products, fostering the resilience of urban infrastructure.

2.2. Challenges to be overcome in the simplification of the DEWS test

Despite technological advancements and the evident potential for industrial application, the simplified DEWS test is not yet a standardized method under current national or international guidelines. For quality control purposes, the K adjustment coefficients discussed in this chapter do not need to be applied, as they are already incorporated into the calibration curve that correlates the tensile properties obtained in the DEWS and 3PBT tests. However, significant challenges remain in defining design criteria using the simplified DEWS, especially regarding factors such as the rigorous technical validation of the K calibration factors, the consistency of the piston displacement control model, and the modification of the constitutive models currently prescribed in national and international standards (ABNT, 2021c; fib, 2024). The current database, although promising, is still too limited to guarantee the full representativeness of these factors across a wide range of mix designs, fiber geometries, and concrete strength classes, in addition to the factors associated with the calculation models currently employed. Thus, the consolidation of this test as a routine quality control tool presents great potential for future standardization by bodies such as ABNT, whereas its application to structural design remains more restricted and depends on further investigation and on adjustments to the constitutive models that are currently calibrated for the use of the 3PBT.

In this context, a critical technical aspect that remains a scientific gap and needs to be systematically investigated is the influence of the loading rate (testing speed) on the post-cracking responses obtained. In current laboratory practice, a rate of 0.12 mm/min is adopted as a reference (Borges et al., 2019), which results in an average testing time of 20 to 30 minutes per specimen. For large-scale infrastructure works, which demand fast quality control and a high volume of samples, this testing time can represent a severe operational bottleneck. Therefore, evaluating the technical feasibility of accelerating the procedure without compromising the reliability of the extracted mechanical parameters is a fundamental step toward making the method more applicable to field practice and the construction site.

The investigation of higher loading rates in the test aims to identify how increasing the piston displacement rate affects the stability of the cracking process and the energy

dissipation of the composite. The primary objective of these future investigations must be to establish safe testing rate ranges, with a significant sample size, that maintain statistical equivalence to the parameters obtained at the rate of 0.12 mm/min. Only through this rigorous validation will it be possible to provide the technical groundwork to consolidate the simplified DEWS test as a viable and efficient alternative to the methods already standardized at the national and international levels.

3. ADVANCES IN THE MECHANICAL EFFICIENCY OF FIBER-REINFORCED CONCRETE

The behavior of SFRC is fundamentally governed by the interaction at the interface between the fiber and the cementitious matrix, since the stress transfer mechanisms after crack formation depend directly on the bond properties and anchorage (Serafini et al., 2018; Figueiredo; Monte; Bitencourt Jr., 2022; Mineiro et al., 2022). The efficiency of this transfer defines crucial properties for the composite, such as residual tensile strength, toughness, and crack opening control, which makes the modification of this interface a promising field for the optimization of fiber-reinforced concrete.

Recent literature has intensively explored the use of surface treatments on steel fibers to enhance the performance of cementitious composites, with a predominant focus on ultra-high-performance concrete (UHPC) matrices. Recent studies investigated the chelating effect of ethylenediaminetetraacetic acid (EDTA) on the surface morphology of the fibers, demonstrating that the removal of metallic oxides and the increase in roughness at the microscopic scale favor mechanical and chemical bonding with the matrix (Kim; Choi; Yoo, 2020; Yoo et al., 2021). However, EDTA exposure times longer than six hours were found to induce excessive corrosion, resulting in premature failures and a reduction in energy dissipation during pull-out. In addition, researchers confirmed that the more active metallic surface generated by EDTA acts as an effective base for anchorage, although the fiber embrittlement caused by the chemical treatment requires strict process control so as not to compromise the ductility of the system (Jang; Yoo, 2022).

The deposition of silica nanoparticles ($nSiO_2$) is another interfacial refinement strategy, as documented in the literature (Pi et al., 2019; Oh et al., 2021). In these investigations, the nanosilica coating applied to steel fibers in UHPC matrices promoted a pozzolanic reaction with the local calcium hydroxide, generating additional calcium silicate hydrate (C-S-H) that fills the pores of the ITZ. This process results in the densification of the microstructure around the fiber, significantly increasing the frictional shear stress and the total pull-out energy. Pi et al. (2019) demonstrated that using sol-gel methods to create mul-

tilayer coatings of $nSiO_2$ is effective for increasing bond strength at various curing ages, establishing nanomodification as a robust tool for optimizing structural reinforcement.

In addition to steel fibers, the literature has extended the application of nanosilica to other types of reinforcement in high-performance matrices. Ren et al. (2022) deposited $nSiO_2$ on sisal fibers in UHPC and observed a 28% increase in pull-out energy and direct improvements in the toughness and flexural strength of the composite. Similarly, several authors used electrophoretic deposition of nanosilica on carbon fibers, overcoming the original hydrophobic nature of these fibers and tripling the energy required for their extraction from the cementitious matrix (Li et al., 2020; Li; Zhu; Pei, 2024). These advances confirm that the integration of chemical treatments, such as EDTA, with nanotechnological coatings can transform brittle interfaces into highly cohesive regions, although most of these results remain concentrated in high-cost matrices and noncommercial fibers, highlighting the need for validation in conventional concrete systems.

Despite the growing interest in strategies to improve the fiber–matrix bond through surface modifications, a technological bottleneck is observed in the application of these innovations to conventional concrete. Most existing investigations focus almost exclusively on UHPC matrices or on fiber types that are not the most widely used in the construction industry, which limits the direct transfer of these advancements to large-scale infrastructure projects. In normal-strength concrete, the porosity and the characteristics of the ITZ differ significantly from those of high-performance matrices, and there is still a lack of systematic evaluations of how physicochemical treatments can act efficiently under these conditions.

This section brings together the investigations on EDTA and nanosilica treatments applied to commercial hooked-end steel fibers, integrating surface treatment technology into normal-strength and high-strength concrete matrices. The quantitative results presented in this section are derived from Batista (2026) and summarize the technological advancements developed at Universidade São Judas Tadeu. They provide technical grounds to improve mechanical efficiency and potentially reduce fiber consumption per cubic meter, promoting a more sustainable and economical use of fiber-reinforced concrete.

3.1. Advances in the surface treatment of commercial fibers

The efficacy of the surface treatment of steel fibers with $nSiO_2$ was validated through scanning electron microscopy (SEM) analyses, as shown in Figure 5. The analysis reveals that whereas the reference fibers show a surface marked by longitudinal grooves resulting from the drawing process and industrial adhesive residues, the treated fibers exhibit

a profoundly altered morphology. The EDTA pretreatment removed metallic oxide layers and impurities, exposing cavities that increased the effective contact area.

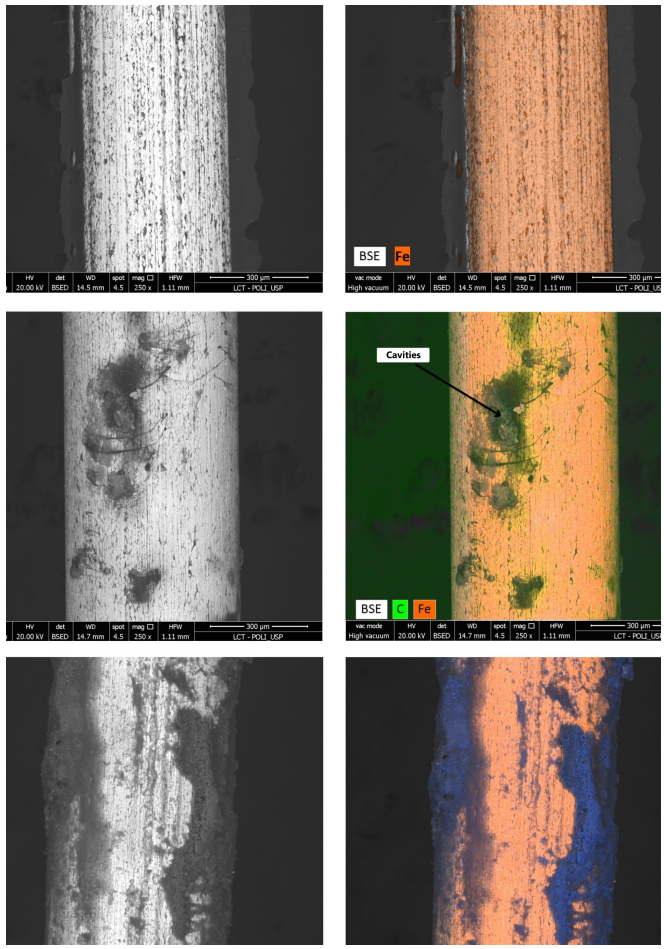


Figure 5 – SEM results with EDS mapping for (a) reference fibers, (b) EDTA-treated fibers, and (c) fibers with $nSiO_2$ deposition.

Source: Batista, 2026.

The subsequent deposition of nanosilica resulted in the formation of an amorphous and continuous coating along the fiber, whose presence was confirmed by energy-dispersive X-ray spectroscopy (EDS), which detected sharp silicon (Si) peaks that were absent in the untreated samples, as shown in Figure 6. This physicochemical modification of the surface translated into significant changes in the pull-out properties, indicating a refinement of the ITZ. In quantitative terms, the treatment increased the peak load (P_{L1}) by 60.8% in normal-strength concrete (NSC) and by 29.8% in high-strength

concrete (HSC), compared with untreated fibers. These results confirm that surface functionalization enhances the load transfer capacity between the fiber and the matrix from the early stages of loading.

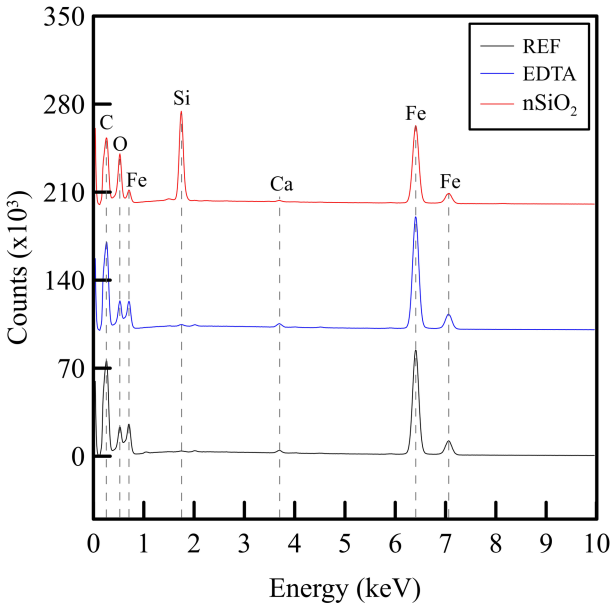


Figure 6 – EDS results for reference fibers, EDTA-treated fibers, and fibers with $nSiO_2$ deposition.
Source: Batista, 2026.

The improvement in interfacial bond was directly reflected in the post-cracking behavior, although the results demonstrated a critical dependence on the matrix strength class. In the indirect tensile tests (DEWS) conducted on normal-strength concrete, the nanosilica treatment increased the residual service strength (F_{SLS}) by 35.8%, demonstrating superior efficiency in controlling small crack openings (COD = 0.25 mm). This performance gain suggests that, in conventional matrices, the technology allows for a more effective mobilization of commercial fibers, which supports the possibility of reducing steel consumption per cubic meter without compromising structural design requirements.

The indiscriminate increase in bond, however, can have detrimental effects, especially in fibers with mechanical anchorage, such as hooked-end fibers. The data revealed that the bond promoted by the nanosilica was so strong that it exceeded the tensile capacity of the steel fibers (1,345 MPa), resulting in high fiber rupture rates in the pull-out test: 76.5% in conventional concrete and 100% in high-strength concrete. In the case of HSC, this increased bond was counterproductive, causing reductions of 39.1% in service strength (F_{SLS}) and 47.5% in ultimate strength (F_{ULS}). Because the fibers ruptured

prematurely instead of slipping, the slip-based energy dissipation mechanism was partially suppressed. Therefore, for the commercial hooked-end fiber market, the nanosilica deposition treatment must be adjusted and moderated by calibrating the deposition time or the precursor concentration, so that the bond increases only up to the limit at which the fiber still debonds and slips, dissipating energy rather than rupturing during pull-out.

3.2. Challenges to be overcome in fiber treatment with EDTA and $nSiO_2$

The main technical challenge for consolidating fiber treatment with EDTA and nanosilica is to balance the gain in interfacial bond with the tensile capacity of commercial steel fibers. Experimental results revealed that although nanosilica deposition promotes significant increases in the peak pull-out load (P_{L1})—reaching 60.8% in conventional matrices—this enhanced bond frequently exceeds the strength limit of the steel fibers (1,345 MPa), resulting in premature fiber rupture. For hooked-end fibers, which already possess considerable mechanical anchorage, this excess chemical bond is counterproductive because it suppresses the hook plasticization mechanism and energy dissipation, leading to reductions of up to 47.5% in the ultimate residual strength (F_{ULS}) in high-strength concrete. Therefore, one of the practical challenges is calibrating the treatment intensity for each class of cementitious matrix, ensuring that the reinforcement slips and controls crack opening without rupturing prematurely.

To tailor this bond, the literature and tests suggest exploring distinct treatment processes that allow the surface reactivity to be "dosed." One innovation front consists of modulating the kinetic parameters of the sol-gel method, such as reducing the precursor concentration (TEOS and CTAB) or shortening the nanosilica deposition time by testing periods shorter than the conventional 12 hours, such as 6- or 9-hour windows. In addition, the EDTA pretreatment, although essential for removing oxides and creating microcavities, must be strictly controlled; exposures longer than 6 hours can induce excessive corrosion that embrittles the fiber's cross section, reducing its ductility and favoring cohesive failure. Future interface engineering must, therefore, focus on customized (tailored) treatments, in which high-performance matrices receive fibers with moderate functionalization to avoid brittle behavior, whereas conventional matrices can be optimized with more intensive treatments to compensate for their interfacial porosity.

Another fundamental challenge for industrial viability involves the transition from manual laboratory immersion processes to continuous and automated production systems. The current method requires long resting times and successive washings, which hinders large-scale application in concrete batching plants. Innovation proposals include developing roller-conveyor immersion systems or spray processes, which would reduce the

consumption of solvents and reagents, making the treatment faster and economically competitive. There is also potential for partnerships with the metallurgical industry to produce pretreated fibers directly at the wire-drawing plant, ensuring strict quality control from the source and eliminating the need for processing at the construction site. Overcoming these logistical and processing bottlenecks is essential for interfacial nanomodification technology to move beyond a niche solution for special concretes and become a standard of efficiency and sustainability for conventional infrastructure.

4. CONCLUSIONS

SFRC has established itself as a fundamental material for modern infrastructure, enabling the transition from a brittle material to a pseudo-ductile composite capable of redistributing stresses after cracking. One of the main advances discussed concerns overcoming the logistical and technical limitations of traditional tests, such as the 3PBT and DPT, through the simplification of the DEWS method. The proposal to use direct molding of cubes with preformed grooves and test control via piston displacement proved to be a viable alternative, facilitating quality control in laboratories with limited infrastructure by eliminating the dependence on sophisticated extensometers.

For this simplification to be safely applied in structural design, research has established the need for adjustment coefficients that guarantee the reliability of parameters at the SLS and ULS. Currently available studies indicate average values of K_m close to 1.4, whereas the displacement factor K_d, which adjusts for small inaccuracies in the geometric correlation between the machine stroke and the actual crack opening, showed an average value of 1.05. The determination of design parameters using the simplified DEWS test still requires further study, although some initial results have been presented in this chapter. For quality control applications, however, these coefficients do not need to be applied individually, as they are already incorporated into the calibration curves currently developed to correlate the simplified DEWS results with the equivalent parameters obtained by the 3PBT.

In the field of material efficiency, investigations into the ITZ revealed that the surface treatment of commercial fibers with EDTA and nanosilica ($nSiO_2$) can transform brittle interfaces into highly cohesive regions. The removal of oxides and the induction of pozzolanic reactions on the fiber surface resulted in increases of up to 60.8% in the peak pull-out load in normal-strength concretes, supporting the possibility of reducing steel consumption per cubic meter. Excessive bond, however, is a challenge, especially in high-strength matrices—where it can cause premature fiber rupture and suppress the slip-based energy

dissipation mechanism—requiring future treatments to be custom-calibrated (tailored) for each concrete class.

Finally, the integration of these technological innovations—from the simplification of tests to interfacial nanomodification—aligns civil engineering practice with the UN Sustainable Development Goals, specifically SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production). The modernization of processes and the rational use of resources raise the quality standards of the precast industry and contribute to the resilience and sustainability of urban infrastructure. The path toward the definitive consolidation of these technologies on a large scale now depends on the standardization of the new test procedures, the refinement of calibration coefficients, and the transition of fiber treatment methods to automated industrial systems.

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CHAPTER 5

Contributions to the carbon footprint assessment of sprayed concrete

Alessandra Spinelli Sant'Anna, Ivaldo Silva da Cunha, Renan Pícolo Salvador, Ramoel Serafini, Dimas Alan Strauss Rambo, Carlos Herrera Mesén

1. INTRODUCTION

Cement is one of the most widely traded products in the world today (GCCA, 2026). Concrete, in turn, which has cement as its main constituent, is the second most consumed material worldwide, behind only water (Scrivener et al., 2018). In 2024, national cement production in Brazil reached 65.5 million metric tons (SNIC, 2024). This is a substantial value compared with other products of large worldwide production and consumption, such as meat, which in the same period reached a production of 325 million metric tons (OECD, 2020).

This high production volume, however, has a significant impact on the environment. Currently, the construction industry is the second-largest contributor to greenhouse gas emissions in the world (Scrivener et al., 2018). It is estimated that approximately 5 to 8% of global CO_2 emissions are associated with the cement industry alone (Humphreys; Mahasenan, 2002; Supino et al., 2016; Scrivener et al., 2018). Within the industrial sector, cement plants rank third in CO_2 emissions worldwide.

Within the construction sector, sprayed concrete is an essential technique, applied mainly as a ground support method for tunnels and mines (Bernard; Thomas, 2020). The main difference between sprayed concrete and conventional concrete lies in its spraying application technique, which imposes specific technical and environmental challenges. For structural purposes, accelerators are used at high dosages, ranging from 5 to 12% by mass of cement (Jolin et al., 2015). In addition, the recommended cement content in the literature ranges from 300 to 500 kg/m³, but in practice contents above 400 kg/m³ are

systematically observed (Ikumi et al., 2022). These high values need to be analyzed and optimized for greater eco-efficiency of the process.

In 2021, about 23 million m³ of sprayed concrete were consumed worldwide, 90% of which was applied in infrastructure works (Markets and Markets, 2021). Brazil is the country that leads this technology in South America, with a consumption potential of 1.4 million m³ per year by 2027. Market forecasts also indicate annual growth of approximately 5% in the use of sprayed concrete (Mordor Intelligence, 2025), which demonstrates the relevance of research, development, and innovation in this area for the economic and technological growth of the country.

Although the technology has evolved and new application procedures have been developed over the years (EFNARC, 1996; AENOR, 2007; ABNT, 2012; ÖBV, 2013; ACI, 2016; Concrete Institute of Australia, 2020), none of these documents has been fully accepted for the reliable selection of material dosages (Ikumi et al., 2022). The empiricism of the adopted mix design practices raises doubts regarding compliance with functional performance requirements (Ikumi et al., 2022). Added to this is the inefficiency inherent to the execution process: about 20 to 30% of the volume of applied concrete can be wasted due to the rebound phenomenon (Ginouse; Jolin, 2016).

The use of high accelerator contents contributes to increasing rebound and generates a highly alkaline mist, causing environmental impacts and occupational health problems (AENOR, 2007). Accelerators also contribute significantly to impacts related to embodied energy, toxicity, and CO_2 emissions (Saade et al., 2018). Due to the effect of accelerators on increasing rebound, one of their indirect impacts is carbon emissions; after all, even the rebounded concrete had its inputs produced and transported. Therefore, the emissions related to the rebounded material must be accounted for as a particular parameter of this technique. Consequently, reducing the use of accelerators directly helps lower the carbon footprint.

Studies on CO_2 emissions in the construction sector have therefore become a global priority for developing solutions that reduce environmental impacts. The relevance of creating decision-support tools for professionals in the field is evident. The integration of carbon emission assessment into the functional performance analysis contributes to improving the quality of life cycle assessment (LCA) inventory data, allowing a more accurate and less subjective environmental impact analysis. The development of optimized concrete systems is also expected to contribute to the global action plan and the Sustainable Development Goals proposed by the United Nations (UN).

2. OBJECTIVES

The general objective of this research is to analyze CO_2 emissions in sprayed concrete within system boundaries comprising raw material extraction, material production, and transportation to the application site, referred to as the "cradle-to-site" approach. In order to achieve the general objective, the following specific objectives were proposed:

- To measure the CO_2 emissions of the materials used in sprayed concrete and of their operational processes;
- To analyze how the particularities of the spraying and rebound processes interfere with the carbon footprint, especially in relation to the rebounded material and the accelerator content used;
- To correlate compressive strength data of sprayed concrete with CO_2 emissions;
- To build a tabulated database and propose a functional diagram for the systematized search for information, assisting material selection and decision-making aimed at reducing CO_2 emissions.

3. FUNDAMENTALS OF SPRAYED CONCRETE

Sprayed concrete is a cement-based composite conveyed through hoses and pneumatically sprayed at high velocity onto a substrate of interest (Austin, 1996; Galobardes, 2013). When properly applied, it is a durable structural material with excellent adhesion capacity between concrete, rock, steel, and other existing materials (Austin, 1996; Galobardes, 2013). It may exhibit physical and mechanical properties better than those of conventional concrete with similar composition (Austin, 1996; Dimmock, 2003). This section presents basic concepts related to sprayed concrete.

3.1. Spraying process and mix design

The spraying process, associated with the use of accelerators, allows the material to adhere to the surface without the need for formwork, which requires rapid hardening. Therefore, sprayed concrete is considered a construction process rather than simply a material (Galan et al., 2019). The spraying of concrete is one of the main factors influencing the quality of the product. The main disadvantage of the technique lies in the rebound rate, i.e., the amount of material that does not adhere to the surface at the moment of application, which can reach 30% by mass (Galobardes, 2013). Sprayed concrete can be applied in several situations, such as linings, underground works, slope stabilization, repairs

and structural strengthening, waterproofing, self-supporting elements, and free-form surfaces (Figueiredo, 1993; Galobardes, 2013).

Figure 1 shows the system assembled on site for the application of sprayed concrete. Both scenarios use robust remotely controlled equipment. Currently, with the advancement of research on materials and equipment, sprayed concrete has expanded its field of applications, especially in underground infrastructure for tunnel construction (Salvador, 2016). Given the growth potential of this technique, complementary studies are necessary, especially regarding the optimized mix design to minimize problems in terms of CO_2 emissions.



Figure 1 – Sprayed concrete application system.

Mix design is the appropriate proportioning of the materials according to design performance and economy criteria. For conventional concrete, there are several well-established and widely disseminated methods in Brazil, such as the procedures proposed by the Brazilian Portland Cement Association (ABCP, 2023) and by the Brazilian Concrete Institute (Tutikian; Helene, 2011). However, due to the influence of the spraying process on mechanical strength, it is not possible to use conventional concrete mix

design methods. For this reason, sprayed concrete specifiers commonly request mixes based on previous experience, resulting in some subjectivity regarding compliance with performance criteria (Concrete Institute of Australia, 2020).

The main materials that constitute sprayed concrete are cement, coarse and fine aggregates, water, and admixtures. To improve the mechanical properties, sprayed concrete may also contain additions of other components such as silica fume, fly ash, and fibers (Galobardes et al., 2019; Salvador et al., 2019; Salvador et al., 2024; Jadoon et al., 2025). The main difference from conventional concrete lies in the use of accelerators, which are added at the moment of spraying (Goodier, 2000; Ginouse; Jolin, 2016). The mix design process must ensure that fresh concrete has appropriate workability for pumping and that the hardened concrete meets the mechanical performance requirements of the design (Goodier, 2000; Ginouse; Jolin, 2016).

Currently, there are numerous technical guides that provide guidance on the mix design of sprayed concrete. However, compliance with these prescriptions is voluntary, since only documents regulated by legislation are mandatory (Ikumi et al., 2022). Table 1 summarizes the main worldwide documents related to sprayed concrete mix design, developed by professional bodies (Ikumi et al., 2022).

Table 1 – Main documents related to sprayed concrete mix design

Author	Document	Country
European Federation of Producers and Specialists of Products for Structures (EFNARC)	European Specification for Sprayed Concrete. Guidelines. (1996)	European Union
French Association for Underground Works (AFTES)	Recommendations for the design of sprayed concrete for underground support (2000)	France
European Committee for Standardization (CEN)	UNE-EN 14487-1:2005 Sprayed Concrete - Part 1: Definitions, specifications and conformity (2005)	European Union
Japan Society of Civil Engineers (JSCE)	Technical specifications for concrete structures - 2007 "Materials and Construction" (CH 8) (2007)	Japan
Norwegian Concrete Association (NB)	Sprayed concrete for rock support (2011)	Norway
Brazilian Association of Technical Standards (ABNT)	ABNT NBR 14026:2012 - Sprayed Concrete Specification (2012)	Brazil
Austrian Society for Construction Technology (OBV)	OBV Guidelines for sprayed concrete (2013)	Austria

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Author	Document	Country
American Society for Testing and Materials (ASTM)	ASTM C1436-13: Standard specification for materials for sprayed concrete (2013)	United States
German Institute for Standardization	DIN 18551 Sprayed Concrete - National application rules for the DIN EN 14487 series and rules for the design of sprayed concrete structures (2014)	Germany
Spanish Association for Standardization and Certification (AENOR)	UNE 83607:2014 IN Sprayed Concrete. Recommendations for Use (2014)	Spain
Chilean Cement and Concrete Institute (ICH)	Sprayed concrete - Chilean Guide for sprayed concrete (Ed. 2) (2014)	Chile
Spanish Association of Tunnels and Underground Works (AETOS)	Design, production and application of sprayed concrete in underground works (2015)	Spain
American Concrete Institute (ACI)	ACI 506R-16 - Guide to Sprayed Concrete (2016)	United States
Ministry of Housing and Urban-Rural Development of the PRC (JGJ)	JGJ/T 372-2016 Technical specification for the application of sprayed concrete (2016)	China
Japan Society of Civil Engineers (JSCE)	Technical specifications for tunnels (2016)	Japan
Concrete Institute of Australia (AuSS)	Sprayed Concrete in Australia, recommended practice (Ed. 3) (2020)	Australia
Ministry of Transport, Mobility and Urban Agenda (MITMA)	Structural Code 2021. Annex 9. (2021)	Spain

Over the years, methodologies for the mix design of this type of concrete have been developed, based on dissociated empirical relationships and, due to the degree of complexity for practical application, they have not gained wide acceptance among professionals and specifiers (Ikumi et al., 2022). In practical terms, the mix design of sprayed concrete is entrusted to the capability and experience of the producers. Due to the wide range of applications, these are often not optimized mixes and rely on excessive and costly testing (Ikumi et al., 2022). Figure 2 details the main steps used for practical mix design.

The spraying process of concrete for structural purposes is carried out by the wet-mix process (Zangerle, 1998; Storrie; Bartlett, 2001; Newman; Choo, 2003). Under controlled conditions, water is added in the mixer and, during application, compressed air is used to accelerate the flow. When the concrete is sprayed at high velocity onto the substrate, part of it does not adhere and is rebounded, altering the composition of the first

applied layers which, generally, have a lower amount of coarse aggregate and a higher amount of cement paste (EFNARC, 1999). The wet-mix spraying system produces less dust than dry-mix methods and has a rebound volume below 10% (Austin, 1996; Vandewalle, 2005).

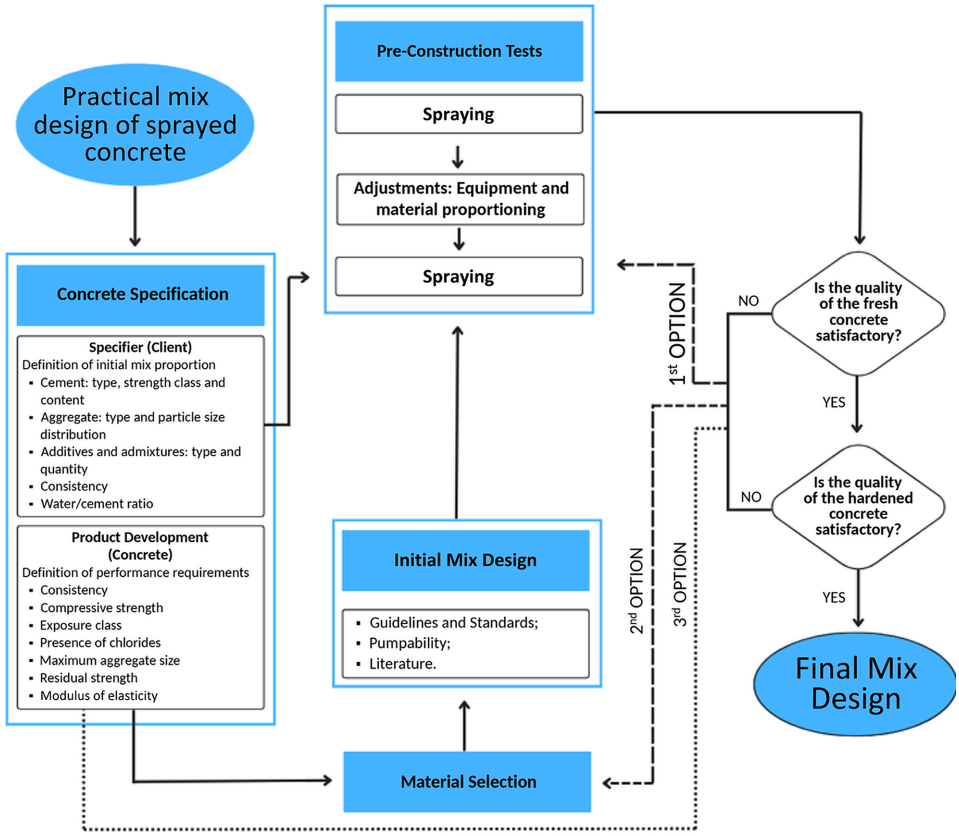


Figure 2 – Flowchart of practical mix design steps.

Source: adapted from Ikumi et al., 2022.

To avoid clogging of the hoses, the accelerators are added at the end of the process, at the spraying nozzle. The hoses must be well lubricated, and the workability of the concrete must be maintained throughout spraying. For this, slump tests are recommended, in which the result should indicate a concrete of fluid consistency, with slump above 20 cm (Galobardes, 2013).

3.2. Mechanical properties of sprayed concrete

Currently, the mechanical properties of sprayed concrete show high dispersion between laboratory and site, due to the great influence exerted by the spraying process (Galobardes, 2013). The mechanical properties of sprayed concrete are mainly affected by the addition of compressed air, rebound (Austin, 1996; Vandewalle, 2005) and the use of high accelerator dosages, which generate porosity in the matrix (Galobardes, 2013).

The mechanical strength of sprayed concrete can be determined at early and late ages, with the values reached in the first hours being particularly important, since they are associated with the safety of the stabilization of rock masses (Galobardes, 2013). Needle penetration and pin penetration tests are used to determine the mechanical strengths reached at very early ages. However, studies and laboratory results on sprayed concrete that ensure the standardization of the material are still lacking (Salvador et al., 2017; Coni et al., 2025).

It is not recommended to apply conventional concrete equations to calculate the mechanical strength of sprayed concrete, since they may produce results that do not reflect practice because they do not account for the effects of the spraying process. The improvement of quality control methods can assist in the adaptation of these equations, aiming at improving the estimation of the mechanical properties for this type of material (Galobardes et al., 2014; Galobardes et al., 2015).

3.3. CO_2 emissions and life cycle assessment

The term environmental performance is defined as the "measurable results of an organization's management of its environmental aspects" (ABNT, 2004), with LCA being one of the techniques employed to fulfill this purpose (ABNT, 2009). Over the last 20 years, LCA has gained international acceptance in the assessment of the entire supply chain of the construction industry (Sharrard et al., 2008). As a result, it has established itself as a fundamental planning tool for sustainability in the sector (Pitt et al., 2009), increasing the competitiveness and productivity of environmentally friendly products (Ortiz et al., 2009).

By encompassing the environmental aspects and impacts involved in the entire process of a product, the scope of LCA is referred to as “cradle-to-grave” (ABNT, 2009). The most critical stage of this methodology is gathering reliable inventory data. Because access to such data is currently quite limited, this restriction is often used to justify omitting detailed discussions about their quality (Ige et al., 2021). In Brazil, there are few standards that regulate LCA, with NBR ISO 14040 (ABNT, 2009) and NBR ISO 14044 (ABNT, 2025) be-

ing available. Methodologically, an LCA comprises four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results (ABNT, 2009).

In environmental terms, LCA contributes to the improvement of the analyzed product at several points along its life cycle. LCA also supports marketing, allowing ecological labeling that adds commercial value to the product, besides acting as an important tool for decision-making in the industry and in public policy issues (ABNT, 2009). In this context, the literature on carbon footprint has become one of the fastest-growing research topics, ranging from industrial operations to theoretical modeling research. These studies promote several benefits, such as stimulating the consumption of sustainable goods through human awareness, improving designs and developing sectors such as environmental energy (Li et al., 2021).

4. METHODOLOGY

For the development of this research, the sprayed concrete compositions previously formulated and characterized in the study of Galobardes (2013) were used. The thesis offers a wide range of data, from the characteristics of the materials to the tests used to determine mechanical performance. Since that study was based on physical and mechanical characterization, this research aims to complement it from an environmental standpoint. In this study, a scenario for calculating material transportation was considered to reflect practical conditions. A field survey was carried out, considering the average distances provided by the main sprayed concrete plant that serves the infrastructure works of Line 6 of the São Paulo Metro. The selected project is an underground infrastructure project, and it was in progress when the research was developed, which facilitated obtaining a larger volume of data.

4.1. Selection of materials for analysis

The materials selected in the study of Galobardes (2013) are presented in Figure 3. For the aggregates, the CO_2 emission values related to transportation were considered, since this is the most significant factor for this material, as the electricity consumption associated with the extraction process is 20 times lower than that associated with cement production (Danielsen; Kuznetsova, 2015). For water, no value was considered, since the concrete plant used as the basis of this study reported that water is supplied by the public network. In this case, there are no emissions related to transportation for this component.

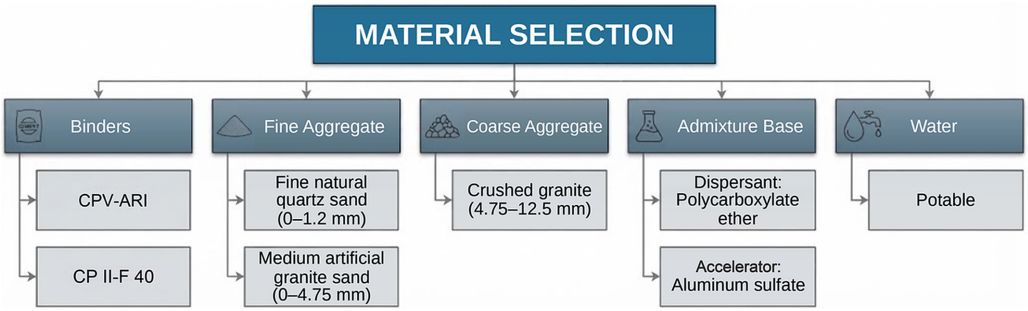


Figure 3 – Materials selected in the base study of Galobardes (2013).

Regarding the binders, the mineralogical composition data were taken from the thesis of Salvador (2016), which determined the values through X-ray diffraction tests and Rietveld refinement. The results of the characterization of the high-early-strength Portland cement (CP V ARI) and the composite Portland cement with limestone filler (CP II-F 40) were summarized in Table 2. From the knowledge of the mineralogical composition of the binders, the CO_2 emission was determined in kg CO_2/t, based on the chemical CO_2 emission data of the clinker compounds plus the share of the calcination process. The CO_2 emission data of the chemical compounds were based on the publication of Scrivener et al. (2018) and on a freely available spreadsheet on the website of the Global Cement and Concrete Association (GCCA), which provides inventory data for the main LCA tools, such as Ecoinvent (GCCA, 2026).

For the CO_2 emission of the dispersing admixtures, a fixed value of 117 kg CO_2/t was adopted and, for the accelerators, the emission of the chemical composition (based on Al2O3 and H2SO4) was combined with the data of the manufacturing process provided by manufacturers. For the accelerators, four types were selected from the alkali-free class. The choice followed the criterion of selecting the compounds that have the greatest availability of mechanical strength data in the thesis of Galobardes (2013), so that it would be possible to carry out the functional performance analysis in comparison with the environmental performance.

The composition of the accelerators was taken from the thesis of Salvador (2016) and is presented in Table 3. To obtain the CO_2 emission data associated with the chemical composition, the spreadsheet available on the website of the GCCA, North American version of the product life cycle inventory version 3.1, was used (GCCA, 2026). The data obtained from the chemical composition were complemented with the CO_2 emission of the production process, estimated at 0.35 kg CO_2/kg (UPC, 2022). The emissions related to the manufacturing process of the accelerators were kept constant and originate from operational processes, such as transportation within the factory plant and packaging.

Table 2 – Mineralogical composition of the CP V ARI and CP II-F 40 cements

Compound	CP V ARI (%)	CP II-F 40 (%)
C_3S	58.3	51.7
C_2S	11.2	6.7
C_3Ac	4.1	2.9
C_3Ao	0.6	0.7
C_4AF	13.4	14.8
CaO	1.1	1.2
$Ca(OH)_2$	1.7	0.7
$CaCO_3$	1.9	11.3
$CaSO_4.2H_2O$	2.1	0.7
$CaSO_4.0.5H_2O$	4.4	5.3
K_2SO_4	-	0.5
$K_2Ca(SO_4)_2.H_2O$	1.1	-
MgO	-	0.6
$MgCO_3$	-	3.1

Source: adapted from Salvador, 2016.

In this study, water was considered to have zero CO_2 emissions, since its supply is carried out directly by the public network at the batching plant, and no emissions associated with its transportation are accounted for. However, this premise is valid only for the conditions adopted in this study, and the corresponding emissions must be included whenever the water supply involves additional stages of abstraction, treatment, or transportation.

Table 3 – Composition of the accelerators

Constituent	Accelerator 1	Accelerator 2	Accelerator 3	Accelerator 4
Al_2O_3 (%)	13.50	12.00	11.20	10.10
H_2SO_4 (%)	21.44	20.00	28.18	22.97
Total solids (%)	34.94	32.00	39.38	33.07

Source: adapted from Salvador, 2016.

4.2. Transportation

The survey of CO_2 emissions associated with transportation was carried out considering two distinct scenarios. In Scenario 1, the distances traveled by the raw materials to

the batching plant were assessed (Figure 4), covering the coarse aggregates, the fine aggregates, and the binders. The corresponding emissions were quantified in the functional unit of kg CO_2/t, given that the transportation of these raw materials occurs in large-scale loads.

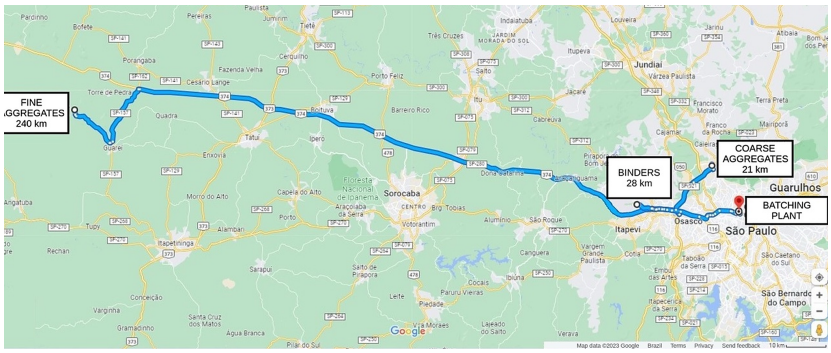


Figure 4 – Stage 1 transportation: Manufacturer-Plant.

In Scenario 2, the distances traveled to the application site were considered, as illustrated in Figure 5, covering the transportation of the ready-mixed concrete from the batching plant to the site, as well as of the accelerators and dispersing admixtures from their respective distributors. The emissions associated with the transportation of the concrete were expressed in kg CO_2/8 m³, corresponding to the maximum loading capacity of a standard concrete mixer truck, while the emissions related to the admixtures were expressed in kg CO_2/kg. To estimate the CO_2 emissions resulting from transportation, diesel oil was adopted as fuel for the trucks, considering an emission factor of 3.2 kg CO_2/L, which covers the manufacturing, transportation, and combustion stages of the fuel, as well as a vehicle consumption of 1 L/km (Carvalho, 2011).

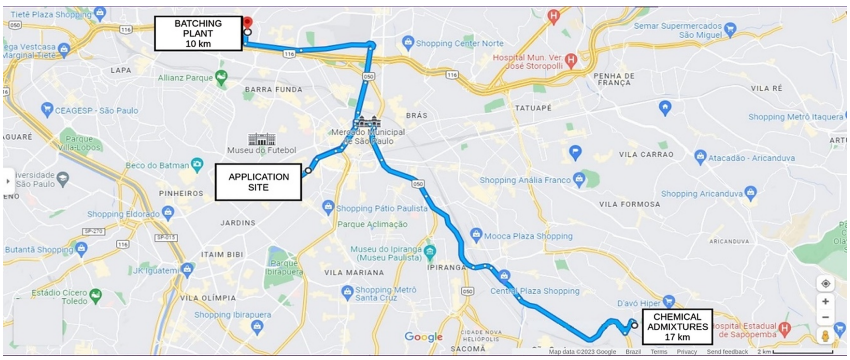


Figure 5 – Stage 2 transportation: Plant/Manufacturer-Site.

4.3. Operational parameters and concrete mix design

For the production of the concrete, some operational parameters were considered, based on the activities of the batching plant. The diesel consumption of the front-end loader, of the concrete mixer truck moving within the plant, and of the pump was added (Santoro; Kripka, 2016).

The concrete mix design was taken from the study of Galobardes (2013) and is presented in Table 4. The contents of the base materials are fixed; only the content of the accelerators varies, as shown in Table 5. The calculation of the CO_2 emissions, from the extraction and production of the materials to the arrival of the concrete at the site, disregarding the accelerators, is presented in Tables 13 and 14. For each material, the emissions associated with its chemical composition, the production process, and the transportation to the batching plant were accounted for. In the specific case of the dispersing admixture, the emission arising from its direct transportation to the application site was also considered. The emissions related to the transportation of the concrete to the site were calculated considering a concrete mixer truck operating at its maximum loading capacity, corresponding to 8 m³. In turn, the emissions from the operational process of the plant and from the transportation of the concrete to the site, since they constitute constant parameters for all the mixes evaluated, were presented separately.

Table 4 – Base materials mix design

Material	Quantity (kg/m³)	Unit Mix
CP V ARI or CP II-F 40	425	1.0
Fine Sand	380	0.9
Medium Sand	900	2.11
Coarse aggregate	380	0.90
Water	190	0.44
Dispersing admixture	4.25	0.010

Source: adapted from Galobardes, 2013.

Table 5 – Accelerator content

Accelerator	Content (% by mass of cement)
1	5.0 / 7.0 / 9.0
2	5.0 / 7.0
3	5.0 / 7.0
4	9.0 / 11.0

Source: adapted from Galobardes, 2013.

4.4. Concrete spraying and the rebound effect

The spraying equipment selected for this study was defined based on the recommendation of the supplier specialized in this type of machinery for large-scale underground works. It is a high-capacity machine, illustrated in Figure 6, that integrates the concrete pump, the remotely controlled spraying arm, and the built-in air compressor into a single system. According to the manufacturer, the machine has a wet-mix sprayed concrete capacity of 33 m³/h (Putzmeister, 2023). The system is powered by a diesel engine, whose nominal power was obtained from the equipment data sheet (Putzmeister, 2023). For the estimation of the fuel consumption, an average consumption factor of 0.15 L/HP.h was adopted for diesel engines, considering an intense operating regime, represented by a power factor of 80%. Thus, the hourly diesel oil consumption was calculated as the product of the nominal power of the engine, the specific consumption factor, and the adopted power factor.



Figure 6 – Spraying machinery selected for the study.

The rebound rates adopted in this research were obtained from laboratory tests. The CO_2 emissions associated with rebound were calculated based on the volume of material lost during spraying, considering all the emissions accumulated in the previous stages of the production cycle, including the extraction and processing of the raw materials, the transportation, the production of the concrete, and the spraying stage itself.

4.5. Mechanical properties

The compressive strength data of the sprayed concrete used in this study were taken from Galobardes (2013). In that study, the strength was determined by the axial compressive strength test of specimens prepared from cores extracted from sprayed concrete panels.

5. QUANTIFICATION OF CO_2 EMISSIONS

5.1. CO_2 emission as a function of binder and admixture type

The breakdown of the calculation of the CO_2 emissions of the binders is presented in Tables 6 and 7. Although the binders have similar compositions, CP V ARI cement emits approximately 12% more CO_2 than CP II-F 40. This behavior is attributed to the lower clinker content present in CP II-F 40, resulting from the incorporation of limestone filler, which reduces the CO_2 emissions from calcination during cement production.

Table 6 – Calculation of the CO_2 emissions of binder CP V ARI

CP V ARI	Mass (t)	Emission (kg CO_2/t)
C_3S	0.583	337.56
C_2S	0.112	57.34
C_3A_C	0.041	20.05
C_3A_0	0.006	2.93
C_4AF	0.134	48.51
CaO	0.011	8.65
$Ca(OH)_2$	0.017	10.11
$CaCO_3$	0.019	0.10
$CaSO_4.2H_2O$	0.021	0.23
$CaSO_4.0.5H_2O$	0.044	0.47
Grinding aid	0.002	3.55
Calcination:		564.00
Total:		**1053.49**

The calculations of the CO_2 emissions of the accelerators are presented in Table 8. From the results obtained, it is observed that the main variation in the emissions among the accelerators is related to the aluminum oxide (Al2O3) content present in their

compositions. However, the manufacturing process represents the largest share of the CO_2 emissions, corresponding, on average, to 66% of the total emitted by the accelerators.

Table 7 – Calculation of the CO_2 emissions of binder CP II-F 40

CP II-F 40	Mass (t)	Emission (kg CO_2/t)
C_3S	0.517	299.34
C_2S	0.067	34.30
C_3A_C	0.029	14.18
C_3A_0	0.007	3.42
C_4AF	0.148	53.58
CaO	0.012	9.43
$Ca(OH)_2$	0.007	4.16
$CaCO_3$	0.113	0.58
$CaSO_4.2H_2O$	0.012	0.13
$CaSO_4.0.5H_2O$	0.053	0.57
MgO	0.006	6.60
$MgCO_3$	0.031	0.16
Grinding aid	0.002	3.55
Calcination		500.00
Total:		**930.00**

Table 8 – Calculation of the CO_2 emissions of the accelerators

Emission (kg CO_2/kg)	Accelerator 1	Accelerator 2	Accelerator 3	Accelerator 4
Al_2O_3	0.18	0.16	0.15	0.14
H_2SO_4	0.04	0.03	0.05	0.04
Manufacturing process	0.35	0.35	0.35	0.35
Total:	**0.57**	**0.54**	**0.55**	**0.52**

Although accelerator 1 presents the highest specific CO_2 emission among the admixtures analyzed, this does not necessarily imply a greater environmental impact in the concrete mix. Owing to the higher Al_2O_3 content in its composition, the required dosages of this accelerator are lower than those of accelerator 4, which may reduce its contribution to the total emissions of the mix.

5.2. CO_2 emission as a function of transportation

The hourly diesel consumption was calculated as the product of the three factors considered, and the results and the respective CO_2 emissions are presented in Table 9. The calculation of the CO_2 emissions per material and per transportation scenario is presented in Tables 10 and 11. It is observed that the fine aggregate presents the greatest contribution to the CO_2 emissions associated with transportation, due to the distances between the aggregate quarries and the consumption sites. In the case of the coarse aggregate, the lowest emission observed is due to the proximity between the supplier and the site analyzed. However, in situations in which the transportation distances are greater, a behavior similar to that observed for the fine aggregate is expected.

Table 9 – Diesel consumption per hour - spraying machinery

Description	Quantity	Unit
Nominal power of the engine	175	HP
Average diesel consumption	0.15	L/HP.h
Power factor	80%	-
Final diesel consumption	21	L/h
CO_2 emission	67.2	kg CO_2/h

Table 10 – CO_2 emissions related to transportation - Scenario 1

Raw Material	Distance (km)	Load (t/trip)	Diesel Consumption (L)	Emission (kg CO_2/t)
Binder	70	32	70	7.00
Coarse aggregate	20.5	23	21	2.92
Fine aggregate	240	28	240	27.43
Water	0	0	0	0
		Total:	**308**	**37.35**

In Scenario 2, the concrete mixer truck presented the greatest contribution to the CO_2 emissions, a result directly related to its lower loading capacity compared with the vehicles used for the transportation of the admixtures. Although Table 11 presents the emissions related to a single trip, the high volume of concrete required by the site demands a significantly greater number of trips by the concrete mixer truck. Consequently, its share in the total emissions tends to be even greater when the transportation required for the entire concreting operation is considered.

Table 11 – CO_2 emissions related to transportation - Scenario 2

Product	Distance (km)	Load (eq/trip)	Diesel Consumption (L)	Emission (kg CO_2/eq)
Concrete	10	8 m³	10	4.00/m³
Superplasticizer	16	15 ton	16	0.003/kg
Accelerator	16	15 ton	16	0.003/kg

5.3. CO_2 emission of the operational processes

The breakdown of the calculations of the CO_2 emissions from the operational processes is presented in Table 12. These values are independent of the concrete mix adopted, remaining constant for all the formulations evaluated. The concrete mixer truck is the main contributor to the CO_2 emissions in the operational stage of the plant, owing to its higher diesel consumption when compared with the other equipment. Since this vehicle is used continuously during the batching, mixing, and transportation stages of the concrete, its contribution becomes predominant in the emissions associated with the operational process.

Table 12 – CO_2 emissions per operational process for the production of 1 m³ of concrete

Operational Process	Diesel Consumption (L/m³)	Emission (kg CO_2/m³)
Front-end loader	0.21	0.56
Mixer truck	2.37	6.33
Pump	0.85	2.27
Total:		**9.16**

5.4. CO_2 emission of the constituent materials of the concrete

The CO_2 emissions of the constituent materials of the concrete are presented in Tables 13 and 14. It is observed that the binders represent the main source of emissions, with the cement manufacturing process being the largest contributor to this environmental impact. The replacement of CP V ARI by CP II-F 40 reduces the total emissions from 500.58 to 448.10 kg CO_2/m³, corresponding to a reduction of approximately 10.5%. This result is directly related to the lower clinker content present in CP II-F 40, due to the incorporation of limestone filler in its composition.

Table 13 – CO_2 emissions for 1 m³ of concrete using CP V ARI

Material	Mix design (kg/m³)	Emission (kg CO_2/m³)
CP V ARI	425	450.71
Fine sand	380	10.42
Coarse sand	900	24.69
Coarse aggregate	380	1.11
Water	190	0.00
Dispersant	4.25	0.50
Plant operational	-	9.16
Site haul	-	4.00
Total:		**500.58**

Table 14 – CO_2 emissions for 1 m³ of concrete using CP II-F 40

Material	Mix design (kg/m³)	Emission (kg CO_2/m³)
CP II-F 40	425	398.23
Fine sand	380	10.42
Coarse sand	900	24.69
Coarse aggregate	380	1.11
Water	190	0.00
Dispersant	4.25	0.50
Plant operational	-	9.16
Site haul	-	4.00
Total:		**448.10**

The calculations of the emissions of the accelerators were carried out individually, owing to the different dosages employed and the variations in their chemical compositions. As presented in Table 15, the emissions from the composition of the admixture, the production process, and the transportation between the manufacturer and the site were considered, the latter being influenced by the dosage used in each formulation.

Although accelerator 1 presents the highest specific CO_2 emission among the admixtures evaluated, accelerator 4, when employed at a content of 11%, results in the highest emission per cubic meter of concrete. This behavior arises from the greater amount of admixture incorporated into the mix, demonstrating that the environmental impact

depends not only on the specific emission of the material, but also on the dosage needed to achieve the required performance.

Table 15 – CO_2 emissions of the accelerators for 1 m³ of concrete

Accelerator	Content (%)	Dosage (kg/m³)	Emission (kg CO_2/m³)
1	5.0	21.25	12.19
	7.0	29.75	17.06
	9.0	38.25	21.93
2	5.0	21.25	11.55
	7.0	29.75	16.17
3	5.0	21.25	11.76
	7.0	29.75	16.46
4	9.0	38.25	20.02
	11.0	46.75	24.47

It is therefore essential to establish mix design procedures that ensure compliance with the performance requirements with the lowest possible amount of admixture. In addition to reducing CO_2 emissions, this strategy avoids the unnecessary consumption of materials, minimizes possible adverse effects on the mechanical properties of the concrete and contributes to reducing production costs.

5.5. CO_2 emission due to rebound

The calculation of the CO_2 emissions arising from rebound considers the volume of material lost during spraying, incorporating the emissions accumulated in all the previous stages of the production cycle, including the production of the materials, the transportation, the operational processes, and the spraying stage itself. The results are presented in Table 16.

It is observed that the highest CO_2 emission was obtained for accelerator 4, employed at the dosage of 11%. This result is directly related to the higher rebound rate presented by this formulation, which implies a greater volume of material lost during spraying. Consequently, there is an increase in the associated CO_2 emissions, since all the rebounded material has already incorporated the environmental impacts arising from the production, transportation, processing, and application stages.

Table 16 – CO_2 emission due to rebound

Accelerator	Dosage (%)	Rebound rate (%)	Emission (kg CO_2)	
			CP V ARI	CP II-F 40
1	5.0	10	51.48	46.23
	7.0	12	62.36	56.06
	9.0	15	78.68	70.81
2	5.0	10	51.42	46.17
	7.0	12	62.25	55.96
3	5.0	10	51.44	46.19
	7.0	12	62.29	55.99
4	9.0	15	78.40	70.52
	11.0	19	99.30	89.33

5.6. CO_2 emission as a function of dosage

CO_2 emissions increase with accelerator dosage, since higher contents of this admixture result in greater material consumption and, consequently, in a greater carbon footprint. In turn, the influence of the dosage on the mechanical performance depends on the age of assessment. In general, higher accelerator contents favor the development of early strengths, but may compromise the strength at later ages.

This behavior is related to the chemical composition of the accelerators and their interaction with the cement. In general, higher aluminum oxide contents promote greater strength gains in the first hours after spraying. However, at later ages, the mechanical performance may be reduced as a function of the compatibility between the accelerator and the binder employed. In the case of CP II-F 40 cement, for example, the presence of limestone filler alters the reactivity of the system, influencing the evolution of the mechanical strengths (Salvador et al., 2016). Thus, the compatibility between cement and accelerator constitutes a fundamental parameter for the performance of sprayed concrete, governing both the evolution of the mechanical strength (Galobardes, 2013; Salvador, 2016) and, indirectly, the CO_2 emissions.

Figure 7 shows that accelerator 3 presented a balance between early performance and strength at 28 days. Although accelerator 2, at the dosage of 5%, presented the lowest CO_2 emission, accelerator 3, employed at the same dosage, presented practically equivalent

emissions and superior mechanical performance, both in the first hours and at 28 days, achieving an additional gain of approximately 6 MPa in the final strength.

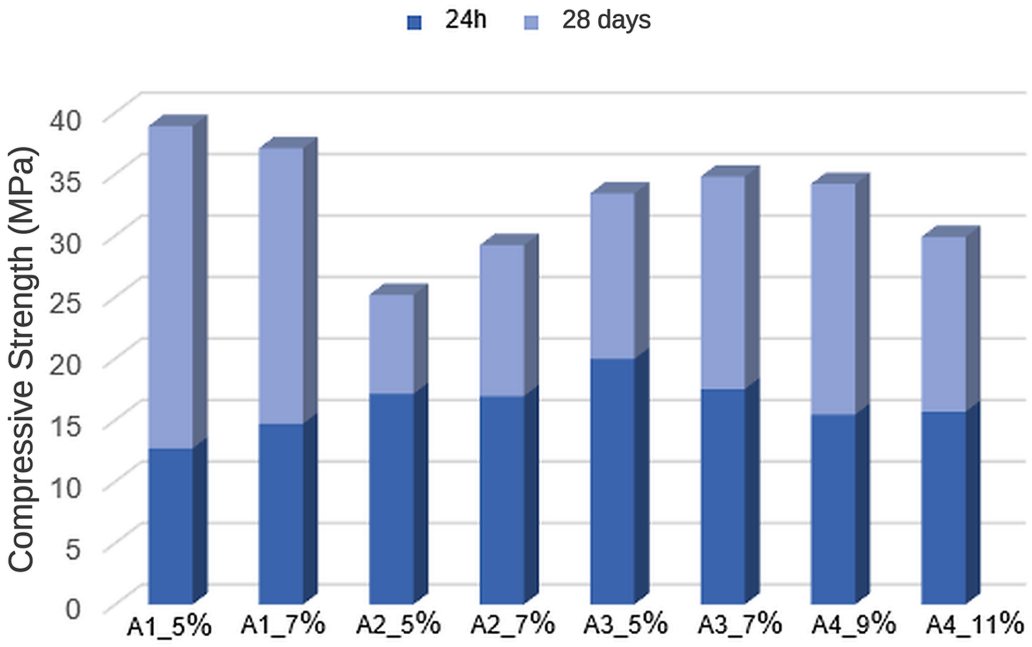


Figure 7 – Differences in the evolution of mechanical strength in relation to the accelerators.

When comparing the emissions presented in Figure 8, it is observed that accelerators 1, 2, and 3 show small differences, since they have similar chemical compositions, are used at equivalent dosages, and have similar rebound rates. On the other hand, accelerator 4 presented the highest CO_2 emission, a result attributed to the higher content used and, consequently, to the greater volume of material lost by rebound during spraying.

The joint analysis of Figures 7 and 8 demonstrates that the choice of the accelerator should not be based exclusively on the lowest CO_2 emission or the highest mechanical performance. Accelerator 3, employed at the dosage of 5%, presented the best balance between CO_2 emission and structural performance, since it kept emissions practically equal to those of accelerator 2, while providing superior mechanical strength both in the first hours and at 28 days.

The correlation between the composition of the formulations, the compressive strength and the CO_2 emissions demonstrates the potential to optimize the selection of the materials. The replacement of binder CP V ARI by CP II-F 40 provides a reduction of approximately 10% in the CO_2 emissions. However, depending on the combination of the binder, the type of accelerator, and its dosage, this replacement may result in reduc-

tions of the compressive strength of up to 32% in the first 24 hours and of up to 49% at 28 days. These results demonstrate that the specification of sprayed concretes should seek a balance between mechanical performance, durability, and environmental impact, with the compatibility between cement and accelerator being one of the main factors to achieve this objective.

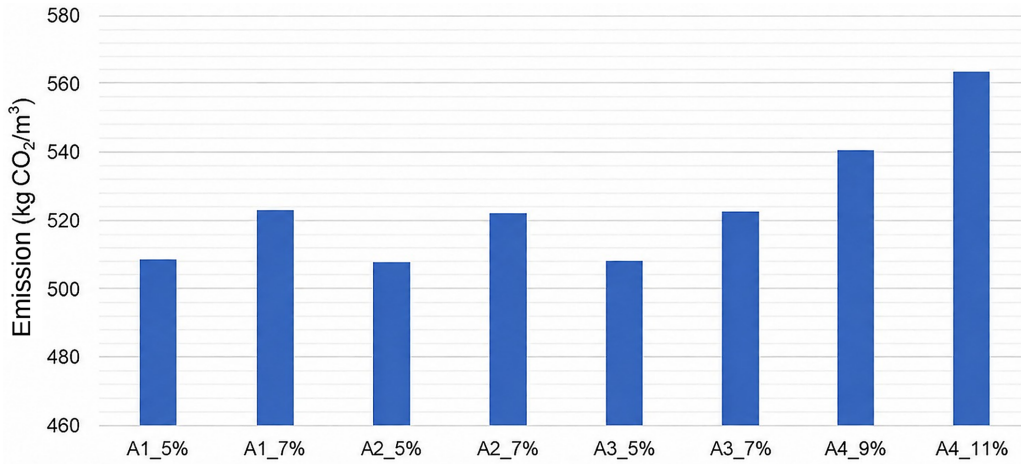


Figure 8 – CO_2 emissions in the formulations using binder CP II-F 40.

6. PROPOSAL FOR MATERIAL SELECTION

Based on the results obtained, the selection of the materials is proposed considering the reduction of the carbon footprint of sprayed concrete. Among the binders evaluated, CP II-F 40 cement proved to be the most promising alternative, providing a reduction of approximately 10% in the CO_2 emissions in all the formulations, owing to the lower clinker content in its composition. However, this cement presented lower mechanical strength than CP V ARI, and the assessment of its compatibility with the accelerator is necessary, since the mineral additions present may exhibit distinct reactivities and compromise the development of the mechanical strengths. The fine and coarse aggregates were kept constant in all the formulations evaluated. Thus, the main contribution of these materials to the CO_2 emissions is associated with transportation. Therefore, the selection of suppliers located close to the concrete batching plant constitutes an effective strategy to reduce the environmental impact.

Regarding the accelerators, their selection should consider the design requirements related to the early and final strengths. Admixtures with lower performance at early ages

may contribute to lower CO_2 emissions and lower rebound rates, although they may compromise the development of the mechanical strength at later ages. Table 17 presents a summary of the main conclusions of this research, with the objective of assisting researchers and specifiers in the selection of materials for sprayed concrete, considering simultaneously the mechanical performance and the reduction of the carbon footprint.

Table 17 – Synthesis of the main results of this chapter

Parameter		Compressive Strength (MPa)		Rebound	Emission (kg CO_2/m^3)
		Initial	Final		
Cement Type	CPV-ARI	⬆	⬆	-	⬆
	CP II-F 40	⬇	⬇	-	⬇
Accelerator Dosage	1_5%	⬆	⬇	⬇	⬇
	1_7%	⬆	⬇	⬆	⬆
	2_5%	⬆	⬇	⬇	⬇
	2_7%	⬆	⬇	⬆	⬆
	3_5%	⬇	⬆	⬇	⬇
	3_7%	⬇	⬆	⬆	⬆
	4_9%	⬇	⬆	⬆	⬆
	4_11%	⬇	⬆	⬆	⬆

7. CONCLUSIONS

This study aimed to analyze the CO_2 emissions associated with sprayed concrete, considering the stages of material production, transportation, operational processes, and rebound, as well as to correlate the environmental impact with the mechanical performance of the different formulations evaluated. The results demonstrated that cement constitutes the main source of emissions, and that the replacement of CP V ARI by CP II-F 40 provided a reduction of approximately 10% in the CO_2 emissions, owing to the lower clinker content. However, this environmental reduction was associated with compressive strength losses that, depending on the combination with the accelerator, reached 32% in the first 24 hours and 49% at 28 days, highlighting the importance of the compatibility between binder and accelerator. The results also showed that the increase in the accelerator dosage, although it favors the development of strength at early ages, raises the CO_2

emissions and the rebound losses, reinforcing the need for the optimization of its dosage. Among the accelerators evaluated, accelerator 3, at the dosage of 5%, presented the best balance between mechanical performance and CO_2 emission. Additionally, the transportation of the aggregates, especially the fine aggregate, and the operations involving the concrete mixer truck proved to be relevant for the carbon footprint. Thus, the results indicate that the reduction of the carbon footprint of sprayed concrete should not be based on the isolated selection of a single material, but on an integrated approach that simultaneously considers composition, dosage, compatibility between the components, mechanical performance, and rebound losses, allowing the specification of more environmentally efficient systems without compromising the performance requirements.

8. ACKNOWLEDGMENTS

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CHAPTER 6

Practical contributions to the use of fiber-reinforced concrete in flooring, pavement, and shotcrete applications

Dimas Alan Strauss Rambo, Renan Pícolo Salvador, Daniela Aparecida de Dutra Lima, Cleber de Souza Amaral, Ramoel Serafini, Rogério Bazan

1. INTRODUCTION

In the Brazilian civil engineering industry, fiber-reinforced concrete (FRC) is widely used in industrial floors and shotcrete tunnel linings, where crack control and energy absorption capacity are critical performance requirements (De La Fuente et al., 2012; Figueiredo; Monte; Bitencourt Jr., 2022). The transition from the use of fibers as secondary reinforcement to their application as primary reinforcement has been driven by advances in constituent materials, including concrete, fibers, and chemical admixtures, as well as by recent developments in key sectors of the Brazilian economy. The expansion of e-commerce, logistics infrastructure, and urban mobility, together with the growth of mining activities and the increasing demand for critical minerals, has intensified the need for concrete structures exhibiting enhanced mechanical performance and durability. Within this context, FRC has emerged as an efficient and reliable engineering solution (Figure 1).

Despite the advances achieved in material development and in the application of FRC, engineering practice still faces challenges related to quality control and the verification of mechanical performance under field conditions (Coronel et al., 2025). In many cases, prequalification testing is conducted in the laboratory using the concrete constituents, admixtures, and fibers specified for the project under controlled mixing, placement, and curing conditions. However, these results are not always confirmed during construction, where variations associated with available materials, mixing procedures, transportation

and placement operations, as well as field conditions and construction equipment, may significantly influence the rheological and mechanical behavior of the concrete.



(a) (b)

Figure 1 – Applications of FRC: (a) logistics warehouse floor and (b) precast tunnel segments.

The absence of adequate quality control measures, particularly with respect to the actual fiber content, residual strengths, and dimensional stability, can introduce uncertainties regarding material performance. In some cases, such deficiencies may contribute to the development of durability and serviceability problems, as well as technical disputes related to the assessment and verification of FRC performance.

In this context, this chapter discusses the main factors governing the mechanical behavior of FRC, with particular emphasis on polypropylene (PP) and steel fibers. It focuses on the properties of the fibers, the cementitious matrix, and the interaction between these constituents. The physical mechanisms associated with post-cracking behavior are examined, along with their relationship to experimental parameters obtained from mechanical testing, particularly those used to evaluate residual strength. In addition, the chapter addresses construction practices and execution procedures associated with the use of FRC in industrial floor applications. Based on this analysis, the chapter aims to provide technical guidance that contributes to a better understanding of FRC performance and supports the more effective application of this composite material in a wide range of civil engineering contexts.

1.1. Objectives

The primary objective of this chapter is to present and discuss the main factors governing the mechanical behavior of fiber-reinforced concrete, with the aim of supporting

its proper application, technical specification, and construction in civil engineering practice. To achieve this overall objective, the following specific objectives are established:

- To present the principal factors influencing the mechanical behavior of FRC;
- To discuss the properties of fibers, the cementitious matrix, and the fiber–matrix interface, as well as their influence on the behavior of FRC;
- To relate material properties to mechanical performance parameters obtained through experimental testing, particularly those defined in ABNT NBR 16940 (ABNT, 2021a);
- To discuss construction procedures employed in FRC industrial floors, including aspects related to mixing, placement, surface finishing, power floating, polishing, and technical qualification through mock-up slabs constructed under field conditions; and
- To provide technical guidance for the practical application and specification of FRC.

2. FUNDAMENTALS OF THE MECHANICAL BEHAVIOR OF FRC

The mechanical characterization of fiber-reinforced concrete can be performed using a variety of experimental methods, each designed to evaluate specific aspects of the material response under loading. Unlike that of conventional concrete, which is often assessed primarily on the basis of compressive strength, the behavior of FRC is governed largely by its tensile response and post-cracking performance. To evaluate these characteristics, several test methods are commonly employed, including direct tensile tests, double-punch tests, shear tests, flexural tensile tests, energy absorption tests, pull-out tests, and the double-edge wedge splitting (DEWS) test.

In the context of Brazilian engineering practice, the flexural and residual strength test prescribed by ABNT NBR 16940:2021 (ABNT, 2021a) has been widely used for the characterization of the mechanical behavior of FRC, particularly in the evaluation of concrete intended for industrial floors, commercial slabs, and urban concrete pavements. For specific applications, such as shotcrete, mechanical performance is often evaluated through energy absorption tests in accordance with ASTM C1550 (ASTM, 2026) or EN 14488-5 (CEN, 2006). Figure 2 presents typical experimental setups for different testing methodologies, highlighting the distinct loading and support conditions adopted in each configuration.

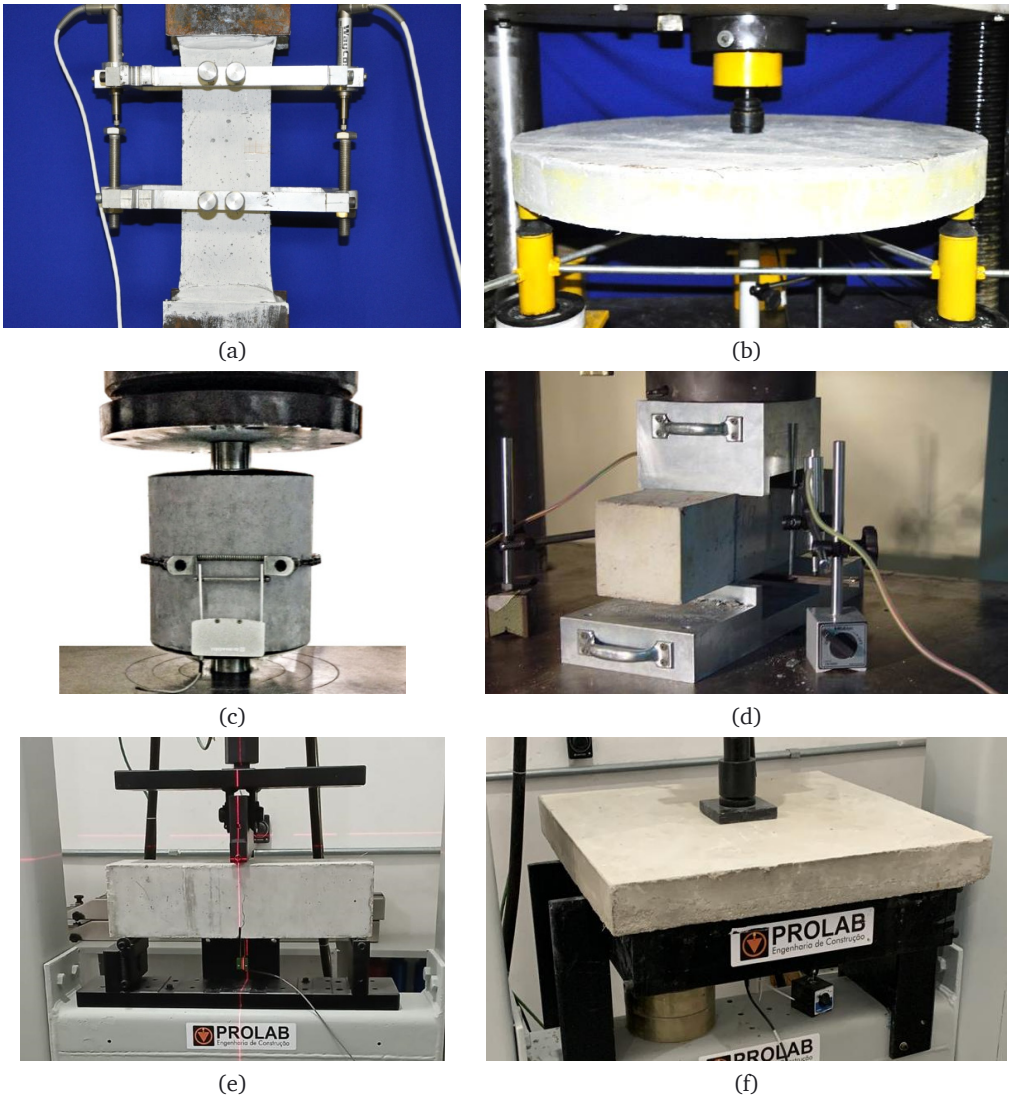


Figure 2 – Methodologies employed for characterizing the mechanical behavior of FRC: (a) direct tensile strength test; (b) ASTM C1550 round panel test (ASTM, 2026); (c) double-punch tensile test; (d) direct shear test; (e) flexural and residual strength test; and (f) energy absorption test according to EN 14488-5 (CEN, 2006).

Source: a), b) Rambo, 2012; c) adapted from Rambo et al., 2018; d) Marangon, 2011; e), f) Courtesy of Prolab.

Figure 3 schematically illustrates the main stages of the mechanical behavior of FRC from the perspective of a three-point bending test performed on a notched specimen, such as that prescribed by ABNT NBR 16940 (ABNT, 2021a) for the determination of residual strengths. In Figure 3(a), a deflection-softening mechanical behavior is observed,

characterized by a reduction in load-carrying capacity after matrix cracking. This response is typically associated with the use of polymeric fibers, even at relatively high fiber contents. In contrast, Figure 3(b) illustrates a deflection-hardening behavior, in which the load-carrying capacity increases after the initial cracking of the matrix. This type of response is commonly associated with the use of steel fibers at high dosage levels.

The mechanical behavior of fiber-reinforced concrete begins with an elastic stage, in which the fibers and the cementitious matrix deform compatibly under low load levels. During this pre-cracking phase, stress transfer between the constituents is governed by interfacial bond mechanisms, a phenomenon described by the shear-lag theory, whereby the fibers are loaded through shear stresses developed along their surfaces (Bentur; Mindess, 2007).

At the typical dosages of polymeric fibers used in Brazilian practice (3 to 6 kg/m³), the contribution of the reinforcement to the initial stiffness of the composite and to the stress associated with first-crack formation is limited, and the behavior is predominantly governed by the properties of the cementitious matrix. A different situation may occur when steel fibers are employed, owing to their high modulus of elasticity (around 210 GPa) and the higher dosages commonly adopted (15 to 25 kg/m³ for industrial floors). Under such conditions, although the matrix still plays a dominant role during the initial elastic stage, the presence of fibers may exert a more noticeable influence on the stiffness of the composite and, consequently, on the strength corresponding to the limit of proportionality (f_{LOP}).

The formation of the first crack marks the beginning of the structural role of fibers in the mechanical behavior of FRC. When the matrix reaches its tensile strength limit, the accumulated energy promotes crack propagation and coalescence. As cracks develop, they intersect the discontinuous fibers distributed throughout the concrete volume. At this stage, the fibers act as stress-transfer bridges across the crack faces, a mechanism known as bridging (Naaman, 2003; Bentur; Mindess, 2007). This action prevents the immediate separation of the matrix fragments, transferring tensile stresses back to the intact portions of the concrete and fundamentally changing the material response from brittle failure to pseudo-ductile behavior (Figueiredo; Monte; Bitencourt Jr., 2022).

The effectiveness of stress transfer through bridging depends critically on the properties of the constituent materials (matrix and fibers), the nature of the fiber–matrix interface, and the interfacial transition zone (ITZ). As the crack opens, a progressive fiber debonding process occurs, followed by fiber pull-out or, in cases of very high bond strength, fiber rupture. For polymeric fibers, frictional sliding during pull-out is the primary energy dissipation mechanism, providing the composite with the residual load-carrying capacity characteristic of FRC. For steel fibers, on the other hand, the frictional sliding

mechanism is complemented by the formation of plasticized zones along the fiber, as observed in twisted or crimped fibers, or in anchorage regions typical of hooked-end or deformed-end fibers. This process contributes significantly to increasing pull-out resistance, since fiber plastic deformation increases the energy dissipated during the extraction process, resulting in a greater stress-transfer capacity and, consequently, improved post-cracking performance of the composite.

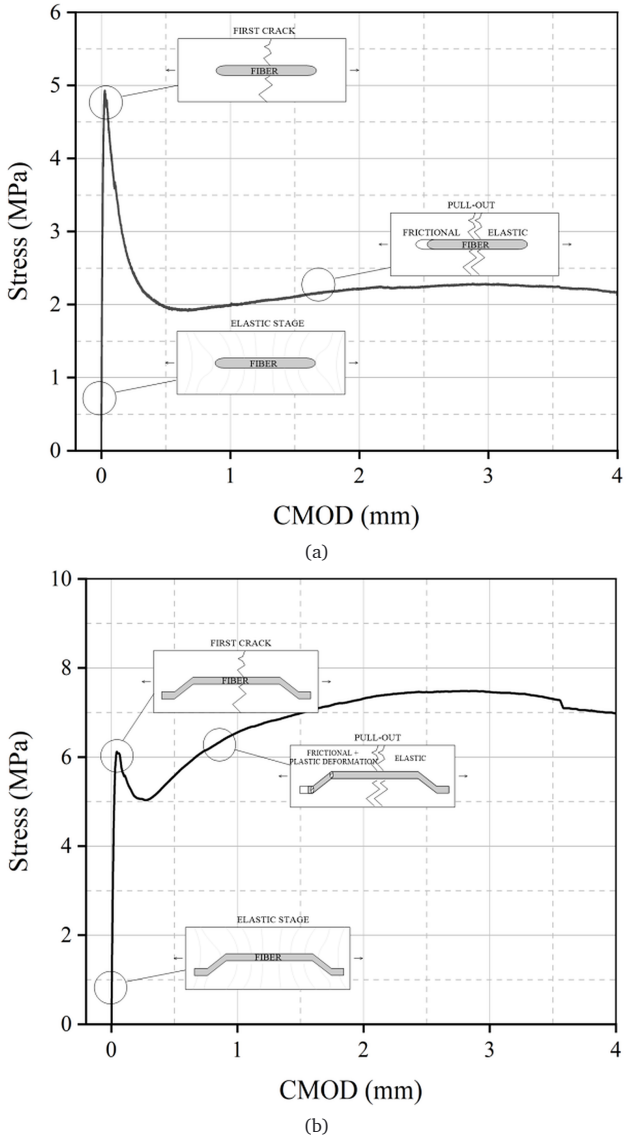


Figure 3 – Stages of the mechanical behavior of FRC in a bending test on a notched specimen: (a) deflection-softening behavior and (b) deflection-hardening behavior.

3. FIBER PROPERTIES

3.1. Fiber type

The engineering of cementitious composites employs different types of fibers to control cracking and modify the post-cracking behavior of the matrices. These fibers may be classified as inorganic (steel, alkali-resistant glass, and carbon), polymeric (polypropylene, polyethylene, nylon, aramid, and acrylic), and natural (cellulose and plant fibers) (Bentur; Mindess, 2007).

Steel and polymeric (synthetic) fibers are the principal types of reinforcement used in structural concrete applications. The high modulus of elasticity of steel fibers (approximately 210 GPa) and their high tensile strength (500 to 2,600 MPa) facilitate stress transfer across cracks formed in the matrix (Figueiredo, 2011). The presence of anchorage mechanisms, such as hooks, crimps, or deformed fiber ends, increases pull-out resistance and contributes to higher residual strengths immediately after first cracking. As a result, steel fiber-reinforced concretes tend to provide greater crack-control efficiency and higher levels of residual strength than concretes reinforced with polymeric macrofibers at the fiber dosages typically used in pavement applications (e.g., 17.5 kg/m³ for steel fibers and 5.5 kg/m³ for polypropylene fibers).

Figure 4 presents typical crack mouth opening displacement (CMOD) response curves obtained for concretes with the same matrix strength (f_{ck}: 30 MPa), comparing a concrete reinforced with 17.5 kg/m³ of hooked-end steel fibers and another containing 5.5 kg/m³ of polypropylene macrofibers. Figure 4 also includes images of the cross sections of 150 mm × 150 mm specimens produced with the respective fiber dosages, allowing visualization of the differences in the number of fibers distributed within the matrix.

In contrast, polymeric fibers, generally composed of polypropylene, have an elastic modulus (3.5 to 11 GPa) lower than that of the cementitious matrix and tensile strengths of approximately 300 to 600 MPa. Despite exhibiting mechanical properties inferior to those of steel fibers, polymeric macrofibers offer important advantages associated with their low density and high number of filaments per unit mass. Whereas steel fibers typically provide approximately 2,000 to 7,000 filaments/kg, polymeric macrofibers may reach values between 70,000 and 200,000 filaments/kg, resulting in a significantly greater number of reinforcing elements distributed throughout the matrix. In typical industrial floor applications, for example, a dosage of approximately 5.5 kg/m³ of polymeric macrofibers may represent about 15 to 66 km of fibers distributed per cubic meter of concrete.

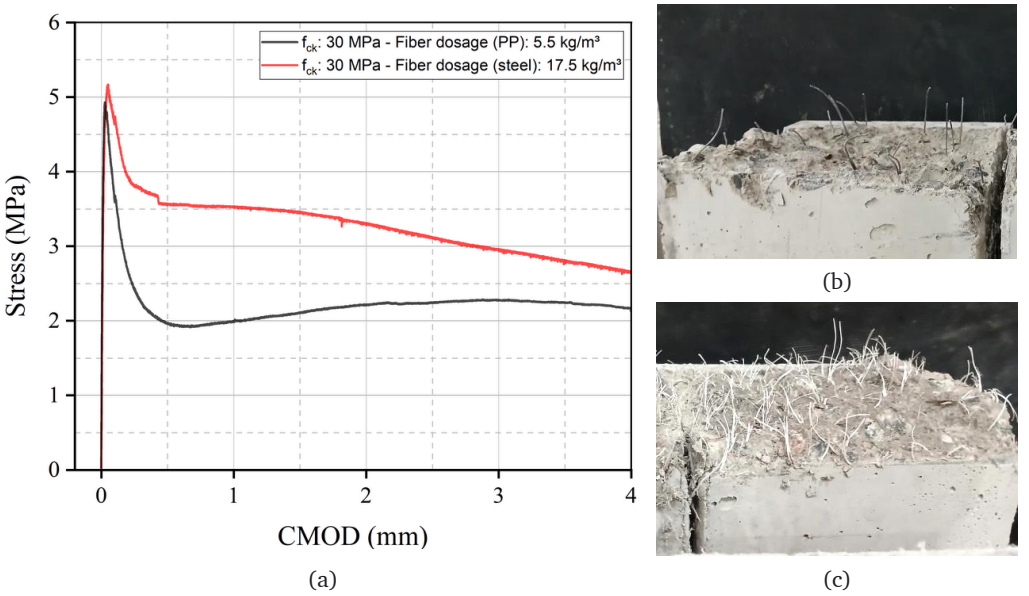


Figure 4 – Comparison of the post-cracking behavior of concretes with the same matrix strength (f_{ck}: 30 MPa) reinforced with hooked-end steel fibers (17.5 kg/m³) and polypropylene macrofibers (5.5 kg/m³): (a) typical crack mouth opening displacement (CMOD) response curves; (b) cross section of a fractured specimen containing steel fibers; and (c) cross section of a fractured specimen containing polypropylene macrofibers.

3.2. Geometry, shape, and processing of fibers

The anchorage of fibers within the cementitious matrix is governed by their geometric parameters, specifically length (L), diameter (d), and aspect ratio (L/d). Whereas straight and smooth fibers depend almost exclusively on chemical/physical bond and interfacial friction, mechanisms that are generally weak in conventional concrete matrices, the introduction of mechanical deformations drastically alters the mechanical behavior of the composite. Steel fibers with hooked ends or crimped configurations utilize the mechanical resistance of the matrix and the plasticity of the metal to dissipate energy during pull-out, resulting in superior stress-transfer efficiency.

Another example of fiber shaping is the twisting process. In the case of steel fibers, twisting is applied to polygonal cross sections (square or triangular) to create helical ribs along the entire length of the filament. This geometry acts as a “screw,” generating a continuous anchorage mechanism that promotes slip-hardening, thereby allowing the composite to sustain increasing residual loads even at large crack openings (Naaman, 2003).

In contrast, in polypropylene macrofibers, twisting serves a predominantly logistical and processing function. Unlike in steel fibers, where twisting enhances mechanical anchorage, in polypropylene fibers twisting is used to bundle multiple filaments together, similarly to glued bundles of steel fibers. When properly designed, this bundling facilitates the homogeneous dispersion of the reinforcement during introduction into the ready-mix truck. In addition, it prevents the formation of fiber agglomerations, technically known as balling, which can impair the workability and uniformity of the mechanical properties of FRC. Once subjected to mixing energy and the moisture of the matrix, these twisted fibers separate into individual filaments or fibrils, ensuring three-dimensional distribution throughout the concrete.

Figure 5 presents examples of polymeric and steel macrofibers with different geometries, shaping processes (such as twisting), and surface characteristics, illustrating solutions used to enhance anchorage mechanisms within the cementitious matrix.

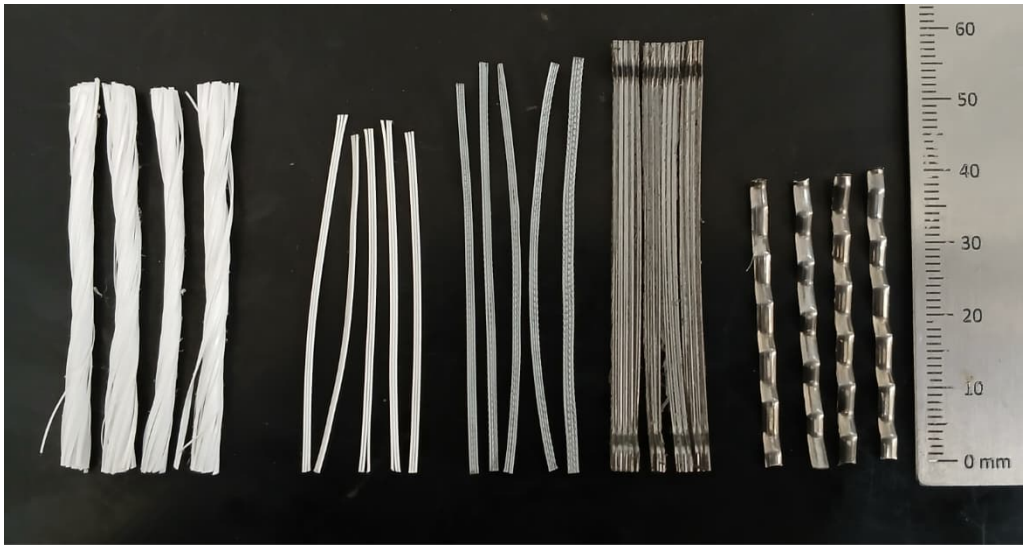


Figure 5 – Examples of fibers used in FRC, including polymeric macrofibers and steel fibers with different geometries, configurations, and surface characteristics.

Figure 6 presents magnified views of the surface of polymeric macrofibers with different surface characteristics, highlighting variations in texture, geometry, and structures capable of being split into filaments with smaller cross-sectional areas.

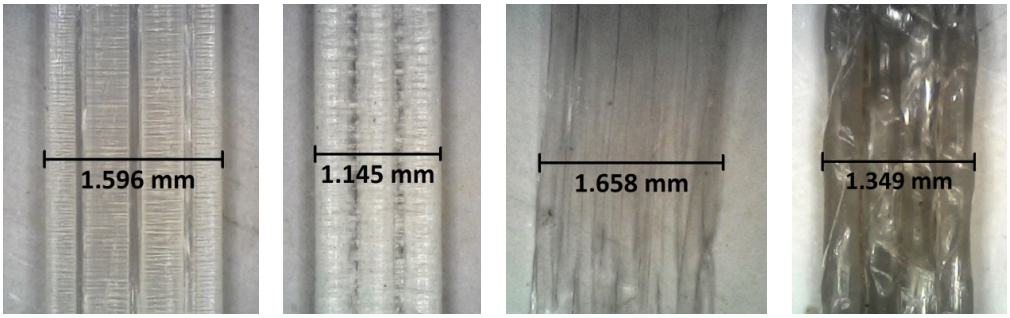


Figure 6 – Magnified views of the surface of polymeric macrofibers used in FRC.

The physical integrity of fibers may also be compromised during the production and transportation of FRC. Polymeric fibers may undergo rupture or fibrillation during intensive mixing, whereas splittable fibers depend on mixing energy to disperse into individual filaments and ensure uniform distribution.

Fibers with very small cross-sectional areas are more susceptible to peeling (surface wear) or premature rupture during the mixing process. The mixing of FRC involves the application of high shear stresses to the fresh mixture, which may cause mechanical damage to thinner fibers. In higher-strength cementitious matrices, the likelihood of fiber rupture, rather than pull-out, tends to increase under mechanical loading. This behavior is particularly relevant in concrete used for industrial floors, where compressive strengths frequently reach values close to 40 MPa.

Fibers with larger cross-sectional areas tend to exhibit different behavior. In such cases, surface peeling may be beneficial, acting as an additional deformation mechanism on the fiber surface. These modifications increase surface roughness and promote the development of mechanical anchorage mechanisms. As a result, improvements in pull-out resistance and stress-transfer efficiency across cracks may occur, contributing to increased composite toughness.

3.3. Fiber dosage

The fiber volume fraction (V_f) or fiber dosage (kg/m³) is one of the fundamental parameters governing the mechanical behavior of FRC, particularly when evaluated by means of flexural tensile tests on notched specimens, as specified in ABNT NBR 16940:2021 (ABNT, 2021a). At dosage levels commonly used in pavements, industrial floors, and shotcrete, the composite exhibits deflection-softening behavior. Under this regime, the load-carrying capacity of the element decreases immediately after the for-

mation of the first crack at the notched section, since the residual contribution of the fibers is insufficient to exceed the cracking strength of the cementitious matrix.

Increasing the fiber dosage beyond the critical volume results in a transition to a pseudo-ductile behavior known as deflection hardening. In the three-point bending test, this phenomenon is characterized by the ability of FRC to sustain increasing or stable residual loads as crack opening at the notch increases.

The mechanical performance of FRC as a function of fiber dosage is often evaluated from the perspective of energy absorption (toughness), a critical parameter for structures such as shotcrete tunnel linings, in accordance with standards such as EN 14488-5 (CEN, 2006). In this type of test, performed on concrete panels (medium-scale tests), the effect of fiber content becomes more pronounced in the load–deflection response, particularly in the area under the load–vertical displacement curve. Increasing the fiber dosage tends to enhance the energy dissipation capacity by promoting the formation and stabilization of multiple cracks. This failure mode differs substantially from that observed in notched-beam tests (e.g., ABNT NBR 16940:2021), in which the mechanical response is dominated by the propagation of a single crack at a predefined location.

Figure 7 presents typical curves obtained for different fiber dosages, illustrating their influence on the mechanical behavior of FRC. In the ABNT NBR 16940:2021 test (ABNT, 2021a; Figure 7(a)), increasing the fiber content is primarily reflected in higher post-cracking residual strengths. In the EN 14488-5 panel test (Figure 7(b)), increasing the fiber dosage results in multiple cracking and, consequently, enhanced energy absorption capacity, as evidenced by the increase in the area under the load–vertical displacement curve.

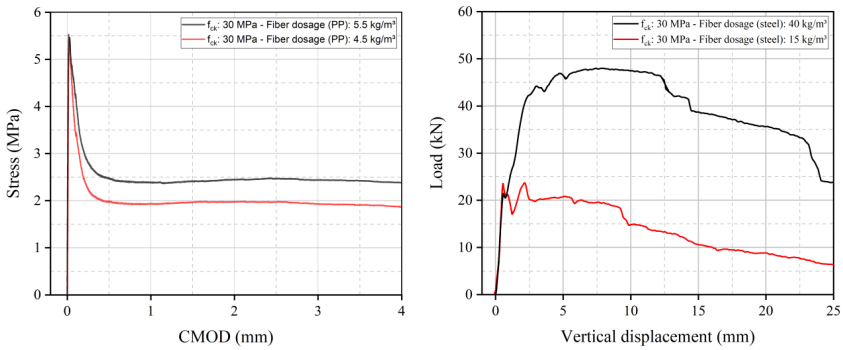


Figure 7 – Influence of fiber dosage on the mechanical behavior of cementitious composites: (a) stress–CMOD response obtained from notched-beam flexural tests in accordance with ABNT NBR 16940:2021; and (b) load–vertical displacement curves obtained from the square panel test according to EN 14488-5 (CEN, 2006).

3.4. Fiber orientation and distribution

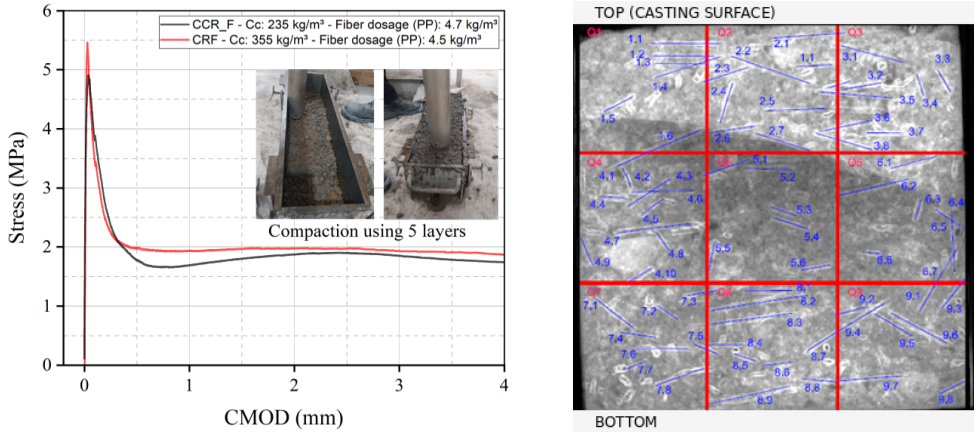
The effectiveness of fiber reinforcement in FRC is highly dependent on fiber orientation relative to the applied tensile stresses, since the load-transfer capacity through bridging is generally maximized when the filaments are aligned parallel to the direction of the applied load (Brito et al., 2021; Montebunhuli et al., 2025). In engineering practice, a perfectly random and homogeneous distribution is rarely achieved, and fiber orientation is governed by mixing, transportation, placement methods, and element geometry.

Fiber orientation is strongly influenced by the wall effect, which is more pronounced in slender elements. In applications such as industrial floors, tilt-up panels, concrete pipes, and certain types of precast segments, the reduced thickness of the element relative to the fiber length physically restricts fiber rotation, inducing a preferentially two-dimensional (2D) spatial arrangement. In addition to geometry, the flow of fresh concrete and the use of injection nozzles during casting may orient the filaments according to the flow direction. A classic example occurs in shotcrete, where the application process propels the fibers against the substrate at high velocity, inducing their alignment parallel to the surface and resulting in a strongly two-dimensional reinforcement structure.

As shown in Figure 8(a), experimental observations on fiber-reinforced roller-compacted concrete (CCR_F) reported by Arruda (2026) also demonstrate that the mechanical compaction process may force the orientation of polymeric fibers into horizontal planes, significantly altering the mechanical response of the composite. Figure 8(a) shows that, despite having a lower cement content (Cc: 235 kg/m³) than a conventional fiber-reinforced plastic concrete (Cc: 355 kg/m³), the CCR_F achieved similar levels of residual strength for comparable fiber contents. This behavior suggests that the fiber orientation induced during compaction increases the efficiency of the reinforcement in transferring post-cracking stresses. Figure 8(b) presents a radiographic image of CCR_F containing polymeric fibers doped with ferromagnetic particles, confirming the preferential orientation of the reinforcement within the cementitious matrix, parallel to the base of the specimen, resulting from the layer-by-layer placement and compaction process.

Unlike polymeric fibers, steel fibers are ferromagnetic, which allows their position to be manipulated through external magnetic fields. Magnetic fiber orientation is currently emerging as a state-of-the-art technology, enabling designers to direct the reinforcement toward regions of the structure subjected to the highest tensile stresses. Recent studies, such as that of Montebunhuli et al. (2025), have investigated robotic magnetic orientation as a strategy for optimizing the reinforcement of concrete elements, ensuring that steel

fibers are not only present in adequate volume within the section but are also positioned at the optimal angle to maximize post-cracking performance and element toughness.



(a) (b)

Figure 8 – Comparison of the mechanical behavior of conventional FRC and CCR_F: (a) stress–CMOD curves obtained from the three-point bending test; and (b) radiographic image of polymeric fibers doped with ferromagnetic particles in CCR_F.

Factors such as internal or external vibration may also induce the orientation of steel fibers within FRC. In magnetic orientation techniques, a controlled level of vibration is required to reduce resistance to fiber movement in the fresh matrix and allow their realignment under the action of the magnetic field. However, excessive levels of vibration may lead to undesirable effects, such as segregation of the constituents, particularly in more fluid mixtures. Because steel fibers have a density approximately three times that of the cementitious matrix, excessive vibration may promote their settlement in the lower layers of the element, resulting in a nonuniform distribution of reinforcement.

3.5. Chemical resistance of fibers in alkaline environments

The durability of FRC is intrinsically dependent on the chemical stability of the reinforcement in the highly alkaline environment of the cementitious matrix. The pore solution of hardened concrete typically exhibits a pH greater than 13, resulting from the concentration of hydroxyl ions (OH^-) released during the hydration of Portland cement (Taylor, 1997). This aggressive alkaline environment acts as a catalyst for degradation reactions in various materials, requiring fibers specified for structural applications to possess chemical inertness or adequate surface protection (coatings) to ensure structural performance throughout the service life.

Conventional glass fibers (E-glass), although not the focus of this chapter, undergo rapid deterioration in this environment, characterized by the breakdown of Si–O–Si bonds. This chemical attack results in mass loss, reduction of filament diameter, and a significant decrease in tensile strength, requiring the use of alkali-resistant (AR) glass fibers, which incorporate zirconium oxide into their composition to retard the progression of corrosion. However, even in AR fibers, durability may be affected by the deposition of hydration products, such as calcium hydroxide, within the spaces between filaments, thereby altering the stress-transfer mechanism.

Among polymeric fibers, polypropylene and polyethylene macrofibers are distinguished by their high chemical stability in alkaline environments, maintaining their structural integrity and tensile strength even after long periods of exposure, as demonstrated by durability evaluation procedures established in standards such as ABNT NBR 16942 (ABNT, 2021b). In contrast, as shown in Figure 9, polymers such as polyester are susceptible to alkaline hydrolysis, a process that promotes molecular chain scission, mass loss, and the consequent gradual reduction of the mechanical properties of the reinforcement.

In this context, it is essential that specifiers verify the composition of macrofibers, since the use of polymeric blends may compromise reinforcement performance. Even small fractions of susceptible polymers, such as PET, introduce vulnerabilities into the fiber reinforcement, affecting the mechanical response due to differences in polymer properties and nonuniform stress transfer.

Additionally, as shown in Figure 9, the alkaline degradation of PET over time results in a loss of fiber cross-sectional area, reducing the effective reinforcement density within the composite. In this case, the durability of the FRC becomes governed by the most sensitive component of the blend, namely the unstable polymer, thereby invalidating long-term performance assumptions.

The effects of chemical degradation on mechanical performance are manifested primarily in the post-cracking behavior (Figure 10). Chemically degraded fibers lose their ability to transfer stresses through bridging, leading to a significant reduction in residual strengths ($f_{R,i}$). Direct fiber degradation may promote a transition in the failure mode from stable pull-out to brittle fiber rupture, resulting in a composite with lower ductility and greater susceptibility to sudden failure. Therefore, the structural durability of FRC depends both on the preservation of the intrinsic properties of the fibers and on the long-term stability of the fiber–matrix interface.

The use of pigments in the manufacture of macrofibers is common practice in the industry. These pigments may be employed either to impart color to the material, for example, by providing gray shades compatible with concrete, or, in some cases, to mask

the presence of polymeric blends. However, the mere presence of pigmentation does not, by itself, constitute evidence of the use of different polymers in the fiber composition.



Figure 9 – Accelerated degradation tests on polymeric fibers: (a) fiber produced from PET (polyethylene terephthalate) and (b) fiber produced from polypropylene.

Source: Salvador; Figueiredo, 2013.

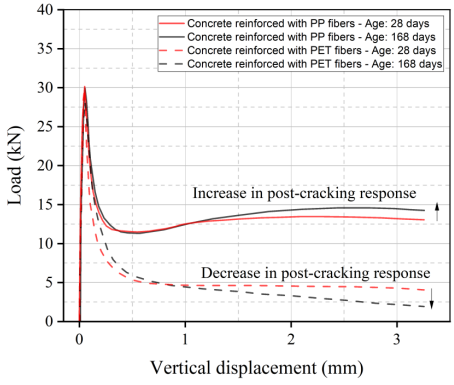


Figure 10 – Comparison of load–vertical displacement curves obtained for concretes reinforced with polypropylene (PP) and polyethylene terephthalate (PET) fibers at 28 and 168 days.

Source: Adapted from Salvador; Figueiredo, 2013.

4. INFLUENCE OF CEMENTITIOUS MATRIX PROPERTIES

4.1. Mechanical properties and fresh-state matrix characteristics

The cementitious matrix plays a fundamental role in the mechanical performance of FRC, acting not only as the predominant volumetric constituent but also as the medium responsible for transferring external stresses to the fiber reinforcement. Initially, the behavior of the composite is governed by the elastic properties of the matrix. Increases in the compressive strength (f_c) and modulus of elasticity (E) of the matrix are directly reflected in an increase in the first-crack stress of the composite.

The influence of the matrix extends critically to the interfacial mechanism, specifically to the ITZ. Increases in matrix strength and stiffness resulting from hydration development, proper curing practices, or the use of mineral admixtures such as silica fume enhance the bond at the fiber–matrix interface. This phenomenon is illustrated in Figure 11, which presents typical stress–CMOD curves obtained from flexural tests performed in accordance with ABNT NBR 16940:2021 (ABNT, 2021a) for the same concrete reinforced with 4.5 kg/m³ of polypropylene macrofibers tested at different ages. Figure 11 compares the responses obtained from two specimens tested at 7 and 28 days, corresponding to matrix compressive strengths of 30 MPa and 46 MPa, respectively. The increase in matrix strength directly influences both the first-crack stress and the initial post-cracking behavior of the composite. For the matrix shown in Figure 11, “CP V” cement was used. For other cement types, however, strength development over time may differ.

Although a stronger bond enhances the stress-transfer capacity at small crack openings, it also alters the failure mode of the reinforcement, increasing the likelihood of fiber rupture during the pull-out process. Because progressive pull-out, which generates bond and frictional stresses, is the primary mechanism responsible for energy dissipation in FRC, excessively strong matrices may, paradoxically, reduce composite toughness. High-strength matrices typically exhibit high residual strengths at small CMOD values. However, they may also show a more pronounced load drop as the crack widens if premature fiber rupture occurs.

The behavior of the matrix in the fresh state is also a determining factor in the mechanical performance of FRC. The fluidity and cohesion of the cementitious matrix control fiber dispersion during mixing and casting operations. Matrices with excessive fluidity and low viscosity may promote reinforcement segregation, particularly in the case of steel fibers, whose density is significantly greater than that of the cementitious matrix, inducing phase separation and settlement of the fiber reinforcement under vibration. In addition, matrices with low mortar content, characterized by a high coarse aggregate content and a low amount of fines, may hinder the dispersion of fiber reinforcement, as illus-

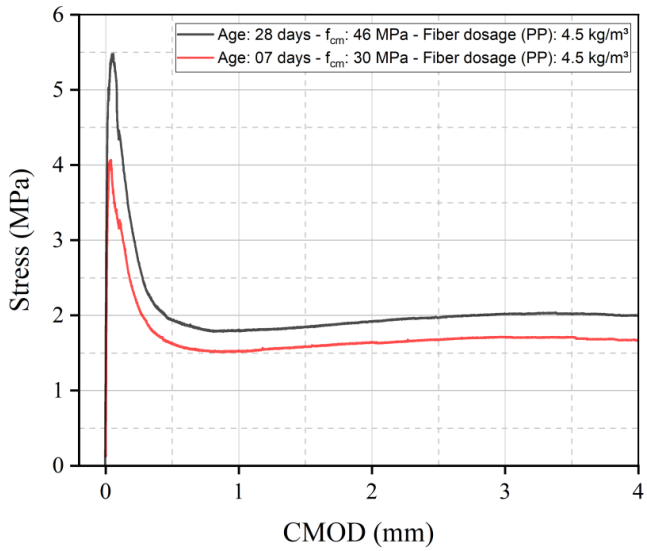


Figure 11 – Influence of matrix strength on the stress–CMOD curve obtained in accordance with ABNT NBR 16940:2021.

trated in Figure 12. In such cases, a greater tendency for fiber agglomeration is observed, particularly for polymeric macrofibers produced through twisting processes, whose bundle separation depends on mixing energy and on the presence of the mortar phase to provide lubrication.

Conversely, matrices with adequate mortar content and rheological properties optimized through the use of superplasticizers and fine additions promote a more stable suspension of the filaments, ensuring uniform distribution and reducing the variability of residual strength test results.

The formation of fiber agglomerations directly compromises the mechanical evaluation of composites, since the nonuniform distribution of reinforcement results in significant variations in the effective fiber content among specimens. In elements containing fewer fibers than the nominal design dosage, residual strengths tend to be underestimated, whereas the localized presence of fiber agglomerations may generate artificially high values.

Figure 13 illustrates the mechanical behavior of three specimens obtained from the same batch of concrete reinforced with 5.0 kg/m³ of polymeric fibers. Specimen CP1 is characterized by the presence of a fiber agglomeration in the fractured section, resulting in an artificially high and unrepresentative post-cracking response. Specimen CP2 exhibits a homogeneous fiber distribution across the cross section, reflecting the expected mechanical performance of the composite. Specimen CP3 shows a reduced effective fiber

content in the load-carrying section due to the formation of fiber agglomerations in other regions of the matrix.

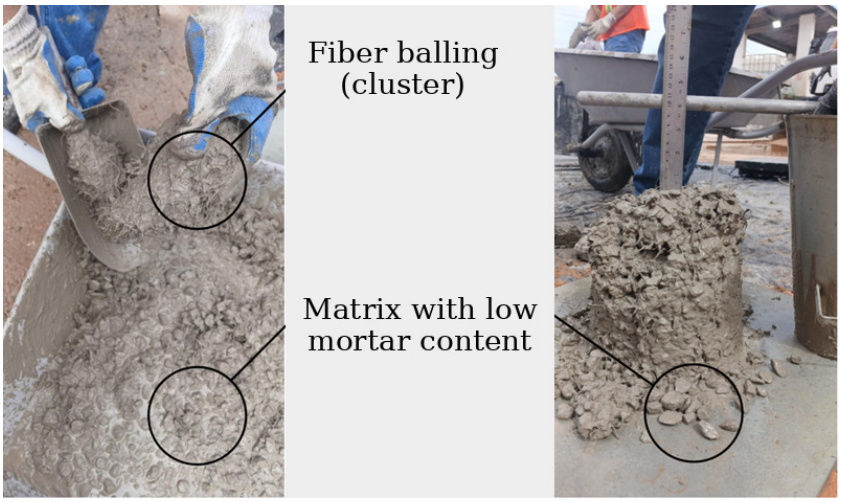
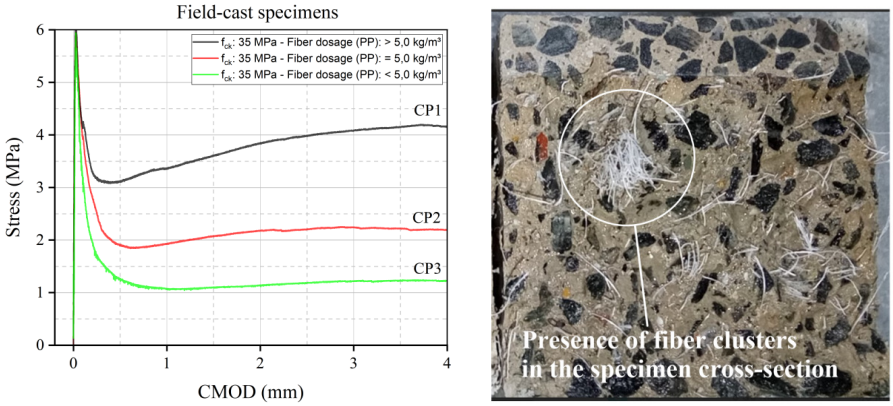


Figure 12 – Formation of fiber agglomerations (balling) in concretes with low mortar content.



(a) (b)

Figure 13 – Influence of fiber content on the mechanical behavior of FRC: (a) CP1, specimen containing a fiber agglomeration (balling) located at the fractured section; CP2, specimen with homogeneous fiber distribution and adequate fiber content; CP3, specimen with reduced fiber content in the load-carrying section due to the formation of fiber agglomerations; and (b) image of a specimen cross section showing the presence of a fiber agglomeration (balling).

In cases such as that shown in Figure 13, which resulted from field testing, the heterogeneity of fiber distribution significantly increases the coefficient of variation of the

experimental results, reducing test reliability and generating uncertainty regarding the properties of the constructed element.

4.2. Influence of shrinkage-compensating admixtures on the mechanical response of FRC

The use of shrinkage-compensating admixtures (SCAs) represents a significant advancement in concrete technology for industrial floors and fiber-reinforced elements, affecting not only dimensional stability but also the microstructure of the fiber–matrix interface. These admixtures, predominantly based on calcium oxide (CaO) or calcium sulfoaluminate, act chemically during the early ages of concrete to mitigate the effects of drying, plastic, and autogenous shrinkage.

The fundamental expansion mechanism occurs through the hydration of calcium oxide calcined at high temperatures, which is transformed into calcium hydroxide ($Ca(OH)_2$), or through the controlled formation of expansive ettringite. Unlike ordinary quicklime, SCAs undergo thermal treatment at temperatures above 1,600 °C, delaying their hydration and allowing expansion to occur in coordination with the stiffness development of the cementitious matrix. This process generates internal expansive stresses, typically ranging from 0.1 to 0.7 MPa, which act to compensate for the subsequent contraction of the material.

The incorporation of shrinkage-compensating admixtures promotes refinement of matrix porosity. The formation of expansive phases assists in filling internal voids, resulting in reduced capillary water absorption and increased compressive strength.

Experimental studies conducted by Donisete (2024) indicate that the incorporation of 12.5 kg/m³ of shrinkage-compensating admixture can increase the 28-day compressive strength by up to 14% relative to the reference matrix. In addition, significant improvements in abrasion resistance were observed, with reductions in abrasion depth on the order of 30% to 45% compared with conventional concretes. This performance is attributed to the mitigation of bleeding and the reduced migration of calcium and sulfur ions to the surface, thereby decreasing the formation of weak and porous layers. According to the author, the modification of cementitious matrix porosity resulting from the use of shrinkage-compensating admixtures also contributes directly to improving the post-cracking behavior of FRC, leading to increases in residual strengths ($f_{R,i}$), in systems reinforced with both steel fibers and polypropylene fibers, as shown in Figure 14.

Analysis of the average curves presented in Figure 14 indicates increases greater than 10% in the $f_{R,1}$ and $f_{R,2}$ parameters for both steel and polymeric fibers, as well as increases of up to 16% in the strengths corresponding to higher crack-opening levels ($f_{R,3}$ and $f_{R,4}$). These improvements allow designers to optimize technical specifications, primarily

by reducing fiber dosage or, alternatively, reducing structural dimensions without compromising the structural safety and durability of the system.

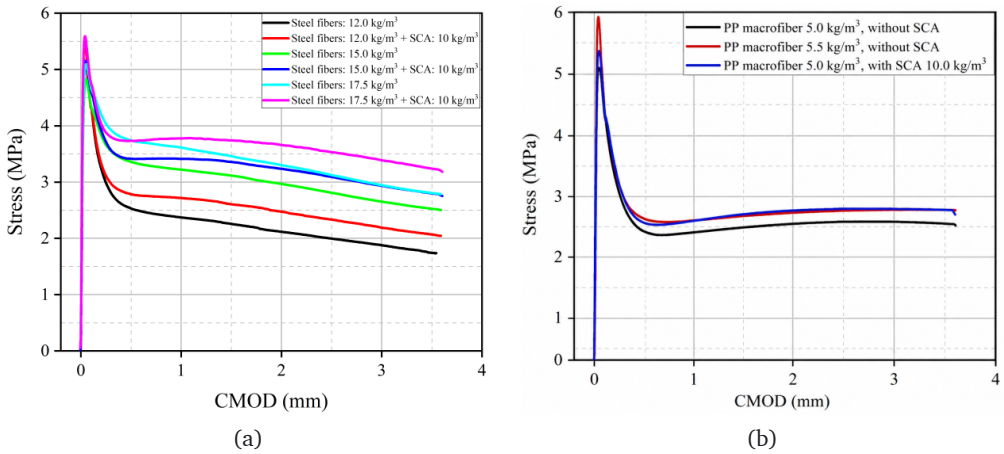


Figure 14 – Stress–CMOD curves obtained from three-point bending tests for concretes with and without shrinkage-compensating admixture (SCA) reinforced with: (a) steel fibers; and (b) polymeric fibers.

5. EXPERIMENTAL EVALUATION OF THE MECHANICAL PROPERTIES OF FRC

The mechanical characterization of FRC requires methodologies that overcome the limitations of conventional compression tests, since the structural benefit provided by fibers is manifested primarily in the post-cracking stage. Unlike plain concrete, which fails catastrophically immediately after reaching its tensile strength, FRC must be evaluated on the basis of its ability to maintain integrity and transfer stresses across cracks.

The fundamental principle of flexural testing on notched specimens consists of inducing a tensile stress state at the bottom fiber of the specimen, thereby enabling monitoring of the transition from the elastic regime of the matrix to the residual regime governed by the fibers. Post-cracking behavior is quantified through residual strengths, which reflect the effectiveness of the crack-bridging mechanism. Whereas the cementitious matrix primarily controls the limit of proportionality and the first-crack load, the fibers provide pseudo-ductility by dissipating energy through frictional slip at the fiber–matrix interface.

In Brazil, ABNT NBR 16940:2021 (ABNT, 2021a) standardizes the three-point flexural tensile test using notched specimens (Figure 15). The procedure is based on the recommendations of RILEM TC 162-TDF (RILEM, 2003) and EN 14651 (CEN, 2007). Spec-

imen preparation requires strict dimensional accuracy. Standard prismatic beams with a cross section of 150 mm × 150 mm and a length between 550 mm and 700 mm must be used for concretes containing aggregates up to 25 mm in nominal maximum size and fibers up to 60 mm in length. Alternatively, when fibers with a maximum length of 40 mm and aggregates with a nominal maximum size not exceeding 12.5 mm are used, prismatic specimens with a nominal cross section of 100 mm × 100 mm and a length of 400 mm may be employed.

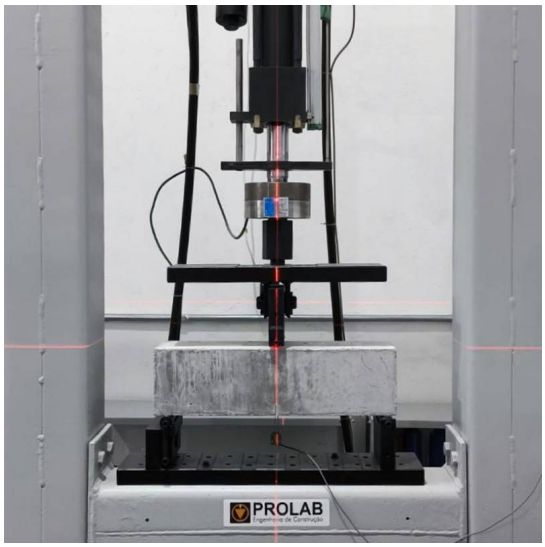


Figure 15 – Flexural and residual strength test.
Source: Courtesy of Prolab.

For mold filling, the standard prescribes specific volumetric increments, with concrete placements in the central region being twice the volume of those placed along the sides. After approximately 90% of the mold volume has been filled, vibration must be initiated, followed by completion of filling and surface leveling. Consolidation must be performed exclusively by external vibration to prevent artificial preferential fiber orientation that may result from the use of internal vibrators. Curing must be conducted in accordance with ABNT NBR 5738:2015 (ABNT, 2015), at a temperature of (23 ± 2) °C and a relative humidity greater than 95%. The specimens must be removed from the protected curing environment between 3 h and 24 h before testing.

A critical aspect of the method's sensitivity is the execution of the central notch, which must have a maximum width of 5 mm and must be produced using an abrasive saw after rotating the specimen 90° about its longitudinal axis relative to the casting position. This

configuration ensures that crack propagation occurs through a section where the fiber distribution is more representative of the overall specimen volume. The distance between the notch tip and the top surface of the beam, designated as *hsp* or ligament, must be maintained at 125 mm ± 1 mm for standard beams. This dimension constitutes an essential geometric parameter for the calculation of residual stresses (ABNT, 2021a).

The test setup consists of one loading roller and two cylindrical steel support rollers with a minimum hardness of 55 HRC, positioned to provide a clear span of exactly 500 mm. To ensure that the applied forces remain strictly perpendicular to the specimen and free from eccentricities, ABNT NBR 16940:2021 (ABNT, 2021a) establishes essential degrees of freedom within the loading system. The support rollers must be capable of rotating freely about their own axes, and at least one support roller must also be free to rotate within the plane perpendicular to the longitudinal axis of the specimen. In addition, the loading roller must likewise be free to rotate within this same perpendicular plane, thereby ensuring proper accommodation of surface irregularities and preventing the development of axial forces or horizontal restraints that could artificially increase the measured residual strengths.

Experimental studies conducted by Rambo et al. (2023) indicate that the absence of support rollers capable of allowing free horizontal displacement, as required by ABNT NBR 16940:2021 (ABNT, 2021a), significantly alters the post-cracking mechanical response of fiber-reinforced concrete containing polymeric fibers (Figure 16).

When the specimen is restrained, the energy required to promote crack opening increases due to friction and the development of horizontal reactions at the supports, resulting in residual strength values significantly higher than those obtained under pure bending conditions. From an engineering practice standpoint, this variability is critical, as it may lead to an overestimation of the material's structural capacity during design. Therefore, ensuring free movement at the supports is not merely a code compliance requirement but an essential condition for the test to accurately capture the fiber crack-bridging mechanism and the actual load redistribution capacity of the cementitious matrix.

Test execution must be conducted exclusively using closed-loop testing machines operated under constant-rate CMOD control. The Brazilian standard specifies a two-stage loading protocol: the CMOD must increase at a constant rate of 0.05 mm/min until reaching 0.1 mm, after which the rate must be increased to 0.20 mm/min until completion of the test, which must not occur before a CMOD of 4 mm is attained. This control procedure is necessary to prevent system instability following the peak load, a phenomenon frequently observed in FRC tests performed using open-loop systems, where control is based on piston displacement or loading rate rather than direct crack-opening measurements (Figure 17).

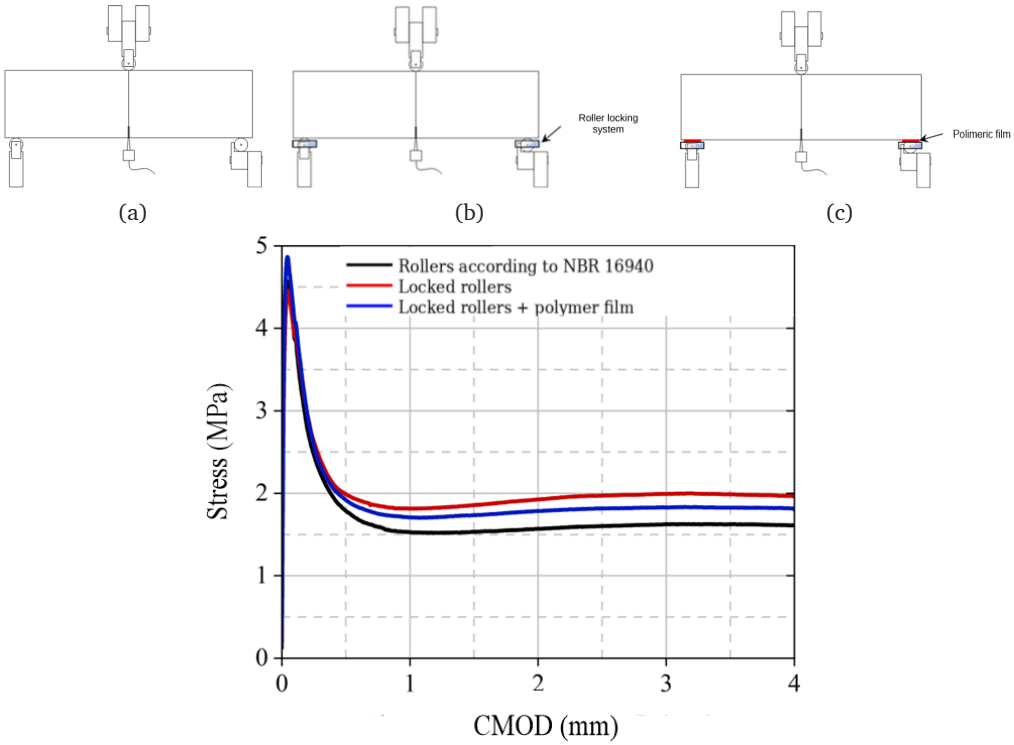


Figure 16 – Influence of the test setup on the flexural and residual strength of FRC: (a) support rollers compliant with ABNT NBR 16940:2021 (ABNT, 2021a); (b) restrained support rollers; (c) restrained support rollers with the insertion of a polymeric film between the rollers and the specimen; and (d) average stress–CMOD curves for the three roller configurations evaluated.

If displacement control is performed using the vertical deflection (δ), a rigid frame known as a yoke must be used. The yoke is attached at mid-height of the beam in the support region to eliminate seating and system deformations that are not part of the material response. As illustrated in Figure 18, the interpretation of test results according to ABNT NBR 16940:2021 is based on the identification of specific points along the stress–CMOD curve. The limit of proportionality (f_{LOP}) is calculated from the maximum load recorded within the CMOD interval between 0 and 0.05 mm. Beyond this point, the post-cracking behavior is characterized by the residual flexural tensile strengths ($f_{R,i}$), determined at CMOD values of 0.5 mm ($f_{R,1}$), 1.5 mm ($f_{R,2}$), 2.5 mm ($f_{R,3}$), and 3.5 mm ($f_{R,4}$). These parameters enable the classification of FRC according to its load-carrying capacity at large crack openings and are fundamental for the design of structural elements such as slabs and tunnel linings, where moment redistribution capacity depends on the residual strength provided by the composite.

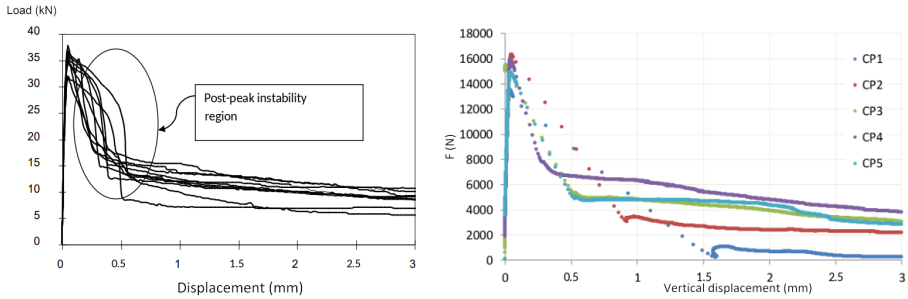


Figure 17 – Load–displacement curves illustrating post-peak instability associated with the use of an open-loop control method.

Source: (a) Figueiredo; Ceccato; Torneri, 1997; (b) Monte; Toaldo; Figueiredo, 2014.

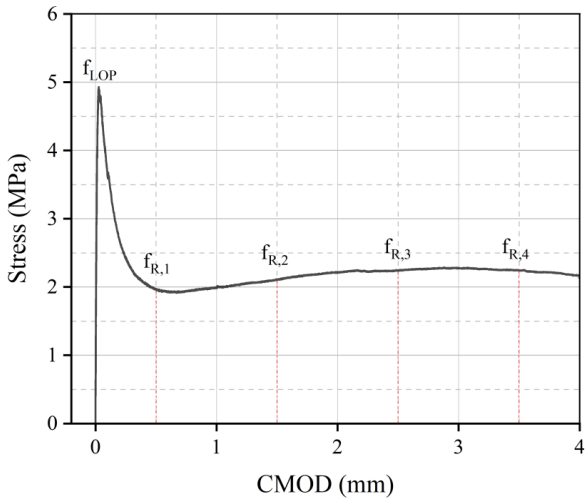


Figure 18 – Typical FRC stress–CMOD curve obtained in accordance with ABNT NBR 16940:2021, showing the identification of the limit of proportionality stress and the residual strengths.

6. CONSTRUCTION PROCEDURES FOR FRC INDUSTRIAL FLOORS

The construction of polished fiber-reinforced industrial floors, whether reinforced with synthetic macrofibers or steel fibers, requires more stringent quality control than that typically adopted for conventional concrete. The presence of fibers modifies the rheological properties of the mixture and directly influences its behavior during placement and finishing operations. Synthetic macrofibers, characterized by a density close to

that of water (approximately 0.91 g/cm^3) and a high specific surface area, tend to affect workability, mixture stability, and surface finish quality. In contrast, steel fibers, owing to their high density, exhibit a greater tendency toward settlement, thereby influencing the distribution of reinforcement throughout the cross section in a different manner. In both cases, even minor variations in construction procedures may result in segregation and nonuniform fiber distribution.

6.1. Mixture control

The formation of fiber agglomerations (fiber balls) is one of the primary deficiencies associated with the mixing stage of FRC and compromises material uniformity. This phenomenon may occur in both synthetic macrofiber-reinforced and steel fiber-reinforced concretes; however, it is more frequently observed with polymeric fibers due to their lower stiffness and higher specific surface area. Fiber ball formation is predominantly related to the method of fiber addition and to inadequate mixture fluidity, both of which hinder proper fiber dispersion. The problem may be further aggravated when fibers exhibit unsuitable geometry or configuration.

In practice, fibers should be introduced continuously and gradually, preferably during aggregate charging, to minimize the formation of initial agglomerations. Dispersion efficiency depends directly on the mixing time and mixing energy provided. In the absence of specific manufacturer recommendations, sufficient mixing energy must be ensured to achieve complete fiber dispersion and prevent the formation of agglomerates. For ready-mix truck mixers, this requirement is typically achieved with mixing times on the order of 1 minute per cubic meter of concrete, although the actual duration may vary depending on fiber type, mixture consistency, and operational conditions. Insufficiently homogenized mixtures exhibit localized regions of elevated fiber concentration, resulting in poor fiber–matrix interaction and reduced efficiency of the stress-transfer mechanism following cracking.

6.2. Placement

Owing to their density, synthetic macrofibers tend to migrate toward the surface, particularly in mixtures with significant bleeding or when subjected to excessive vibration. This behavior differs from that observed in steel fibers, which generally tend to settle within the concrete mass.

The use of equipment such as a vibrating screed or laser screed is required to ensure adequate consolidation and surface leveling. Vibration temporarily reduces the viscosity of the cementitious matrix, allowing fiber repositioning and promoting the formation of

a surface layer with a higher mortar content. Excessive vibration or mixtures with high water content may result in segregation and fiber accumulation at the surface, thereby impairing finishing operations. In addition, preferential fiber orientation within the horizontal plane may occur, altering the mechanical response of the composite and potentially affecting the surface appearance. The use of shrinkage-compensating admixtures may contribute to reducing bleeding and improving mixture stability, thereby facilitating fiber reincorporation during placement and initial finishing operations.

6.3. Finishing and surface polishing

The timing of mechanical finishing is a critical factor governing the surface performance of the floor. The application of cementitious dry-shake hardeners contributes to increased abrasion resistance and promotes the formation of a surface layer with a higher paste content, thereby enhancing fiber cover. This material should be applied immediately after screeding, allowing for more effective incorporation into the concrete surface.

During the floating operation, shown in Figure 19(a), steel float pans facilitate the reincorporation of fibers into the surface matrix and assist in transporting mortar toward the floor surface. This operation should begin when the concrete has reached an appropriate consistency, thereby preventing both persistent fiber exposure and premature surface sealing. Delayed floating hinders fiber reincorporation, whereas premature execution may trap bleed water beneath the surface, increasing the risk of delamination.

During the subsequent finishing stages (troweling and polishing; Figure 19(b)), the progressive closure of surface porosity contributes to the encapsulation of fibers within the concrete matrix. When the process is properly controlled, the fiber reinforcement does not adversely affect the visual appearance of the floor.



(a) (b)

Figure 19 – Surface finishing stages for FRC floors: (a) floating and (b) polishing.

Source: Courtesy of Alphapiso.

6.4. Technical qualification and mock-up slab

The behavior of fibers during finishing operations depends on their geometric and mechanical characteristics. Polymeric fibers with higher stiffness or monofilament geometry exhibit a greater tendency toward surface exposure and are more difficult to reincorporate into the cementitious matrix. For steel fibers, even more stringent control is required during batching at the concrete plant. These fibers are generally supplied in one of two forms: glued bundles or loose fibers. To ensure efficient dispersion within the concrete matrix, fibers must be introduced onto the conveyor belt continuously and gradually, avoiding placement in large batches. This practice is critical for preventing the formation of fiber balls and ensuring composite homogeneity.

Accordingly, prior validation of the proposed solution through the construction of a mock-up slab is recommended. This procedure allows assessment of workability, fiber dispersion, behavior during finishing operations, and the final surface performance under actual construction conditions. The mock-up slab should serve as the basis for adjusting mixture proportioning, construction procedures, and acceptance criteria, thereby ensuring compliance with both structural and aesthetic performance requirements.

7. FINAL REMARKS

The overall performance of FRC results from the interaction among the cementitious matrix, the fibers, and the ITZ. Whereas the matrix governs the initial stiffness and first-crack strength, the ability of the fibers to transfer stresses across cracks is responsible for the post-cracking behavior, pseudo-ductility, and residual strength of the composite. Therefore, the effectiveness of the system does not depend solely on the individual properties of its constituents but rather on the combined action of these mechanisms at the microscale.

Achieving such performance under field conditions requires strict control of concrete proportioning, mixing, transportation, placement, and finishing procedures. Several factors may impair the effectiveness of fiber reinforcement, including improper fiber incorporation; incompatibilities between fiber geometry and cementitious matrix characteristics; fibers exhibiting a high degree of entanglement (twisting); insufficient mixing time and energy; excessive loss of workability; segregation during transportation or placement; and inadequate consolidation and surface-finishing procedures. As a result, field performance may differ significantly from that predicted during design or observed under laboratory conditions.

In this context, laboratory prequalification plays a fundamental role in reducing risks during construction. Preliminary testing using locally available materials enables the assessment of material compatibility, verification of fiber dispersion, and validation of the expected mechanical performance prior to full-scale production. In addition, the construction of mock-up slabs constitutes an essential field-validation step, allowing the evaluation of concrete behavior under actual production and placement conditions. The combination of laboratory characterization and mock-up slabs significantly reduces the uncertainties associated with the application of FRC, contributing to more uniform and reliable structural performance. Accordingly, the successful implementation of FRC requires an integrated approach combining laboratory characterization, quality control, and sound construction practices, thereby ensuring the performance, durability, and safety of fiber-reinforced concrete structures.

8. ACKNOWLEDGMENTS

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CHAPTER 7

Industrial waste valorization as raw materials for the production of construction materials: practical contributions

Cláudia Terezinha Kniess, Renan Pícolo Salvador, Heloisa Candia Hollnagel, Carlos Alberto Cioce Sampaio, Lucas Maia de Souza, Daniela Aparecida de Dutra Lima, Lucas José Nasraui

1. INTRODUCTION

Although there is awareness of the ongoing civilizational crisis, in which the symptoms of structural social inequality and what was once understood as climate change—but is now a climate emergency—are manifest, the engineering field offers a pragmatic contribution. Such a contribution is important, not least because the meaning of sustainable development will become fully known only when it is achieved (Kniess et al., 2022). Nevertheless, due precautions must be taken to ensure that the use of technology results from a systemic diagnosis, for example, one framed by the pursuit of the Sustainable Development Goals (SDGs) of the 2030 Agenda (ONU, 2015), rather than from a merely partial perspective. This is necessary to prevent something prematurely defined as an innovative solution from ultimately creating a new problem.

The valorization of industrial waste as a raw material for construction materials is an important strategy for the transition of the production sector toward more sustainable, circular, and technologically efficient models (John, 2000). The construction industry is among the economic activities with the highest consumption of natural resources, particularly mineral aggregates, clays, limestone, water, and energy. Simultaneously, several industrial sectors generate waste whose physical, chemical, and mineralogical characteristics are compatible with raw materials traditionally used in the production of concrete, mortars, ceramics, pavements, and composite materials.

Accordingly, incorporating industrial waste into construction materials has the potential to reduce natural resource extraction, minimize landfill disposal, extend the service life of final disposal areas, and add value to materials previously treated solely as environmental liabilities, while also creating competitive advantages for organizations (Pereira et al., 2024). Moreover, such valorization is related to contemporary demands for infrastructure that is more resilient, efficient, and adaptable to climate change. The State of the Nation 2025 report, published by the United Kingdom's Institution of Civil Engineers (ICE), emphasizes that the infrastructure sector faces challenges associated with aging built assets, energy transition, and the need for accelerated decarbonization of urban and construction systems (ICE, 2025). Therefore, alternative materials and lower-impact construction solutions are becoming strategic for both climate mitigation and strengthening the resilience of the built environment.

The discussion of industrial waste in construction should not be confined to the notion of simple reuse or direct substitution of inputs. This is a technical field that requires rigorous characterization, quality control, environmental assessment, and performance analysis (Bonifazi et al., 2025). Each waste stream has a specific composition that depends on the industrial process that generated it, the original raw materials, treatments applied, and storage conditions. Therefore, its application in construction must consider properties such as particle size distribution, specific gravity, chemical composition, hazardousness, thermal behavior, reactivity, leaching, solubilization, compatibility with cementitious or ceramic matrices, mechanical strength, and durability (Souza, 2022). Waste valorization, therefore, cannot be justified by environmental arguments alone; it must demonstrate technical performance and safety in use.

The wastes with the greatest application potential include iron and steel slags, industrial ashes, mining waste, treatment-plant sludge, ceramic waste, foundry sand, stone powder, glass waste, polymers, waste tire rubber, and construction and demolition waste (CDW), which in Brazil corresponds to *resíduos da construção civil* (RCC). These materials may serve as recycled aggregates, pozzolanic additions, fluxes, constituents of ceramic bodies, reinforcements in composites, or partial substitutes for natural raw materials (Brasileiro; Matos, 2015). In many cases, using these wastes helps not only to reduce environmental impacts but also to improve specific material properties, including density, thermal insulation, workability, abrasion resistance, dimensional stability, and performance under particular exposure conditions.

From a practical standpoint, industrial waste valorization brings together three fundamental dimensions: environmental management, technological innovation, and productive development (Akbulut et al., 2025). For industry, it offers an opportunity to reduce costs associated with waste treatment, transportation, and final disposal. In the

construction sector, the availability of alternative raw materials is expanded, and the development of products with lower environmental impact is encouraged. For society, it helps mitigate problems associated with improper waste disposal, degradation of mineral extraction areas, and intensive consumption of natural resources. This integration reinforces the role of engineering as a field capable of transforming environmental problems into technically viable material solutions.

The construction sector is directly related to the achievement of the 17 SDGs of the 2030 Agenda (ONU, 2015), SDG 18 (Ethnic and Racial Equality) of the Brazilian Agenda, and the proposed SDG 19 (Art, Culture, and Communication) and SDG 20 (Rights of Indigenous Peoples and Traditional Communities), discussed by Brazil's National Commission for the SDGs (CNODS) (Cabral; Galvão, 2025). This relationship exists because the sector influences waste generation, greenhouse gas emissions, urban quality, people's living conditions, and the consumption of what is commonly reduced to the term “natural resources.” Although efforts should encompass all 20 SDGs, a recent study conducted within the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu presented the results of the ImpactoSociedade software (NuPIS, 2024). The tool relates the master's theses and doctoral dissertations produced by all CAPES Engineering I graduate programs to their corresponding SDGs. In this context, the sector contributes particularly to SDG 9 by fostering innovation, resilient infrastructure, and more efficient construction technologies; SDG 11 by promoting more sustainable cities and communities; SDG 12 by requiring responsible patterns of production, consumption, material reuse, and recycling; and SDG 13 by demanding action to reduce climate impact. Thus, practices such as energy efficiency, rational use of water and materials, proper management of CDW, reuse of industrial waste, and adoption of lower-impact construction solutions are essential to align the construction sector with the 2030 Agenda and sustainable development.

This chapter discusses the practical contributions of valorizing industrial waste as a raw material for construction materials, emphasizing its application possibilities through studies conducted in the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu (MP-EC/USJT), within the research line “Innovation and Sustainability in the Built Environment.” This chapter seeks to demonstrate that using industrial waste can constitute a concrete pathway for innovation in construction, provided that it is supported by appropriate characterization, experimental design, technological development, and performance assessment.

2. INDUSTRIAL WASTE VALORIZATION

Changes in the international context have prompted organizations to innovate, manage change, and promote the sustainable development of new products and services. This scenario creates new barriers for companies, increasing both the complexity of the challenges and the speed required to maintain and develop their businesses (Martens et al., 2016).

The growth of industrial activity, with the consequent generation of greater quantities of waste and pollutants, together with increasing demand for products and services, has compelled the development of new production-process technologies. Simultaneously, it has created a need for new administrative techniques aimed at managing these activities in a manner consistent with environmental concerns (Barbieri et al., 2010).

Discussions on environmental degradation in international forums, society's demand for socioenvironmental responsibility, and stricter legislation have contributed to consolidating actions that point toward a more efficient approach to solid waste management, encompassing both industrial processes and post-consumer waste.

In response to heightened environmental concerns, industries across different sectors pursue sustainable development by increasing efficiency through the rational use of natural resources, reusing or recycling waste, and adopting alternative raw materials that are less harmful to the environment (Carayannis; Rakhmatullin, 2014).

Industrial systems are supplied with energy, raw materials, and water, which undergo transformations during processing, resulting in products and waste (Schiske; Hagelüken; Steffenhagen, 2005). The study of these material and energy flows in industrial and consumption activities, their effects on the environment, and the influence of economic, political, regulatory, and social factors on resource flows, use, and transformation forms part of what is known as “industrial ecology.”

The growing demand for safe final disposal systems has stimulated research into technological and economic alternatives that allow waste to be introduced as raw materials, fillers, or aggregates in other production cycles. This can reduce treatment and final disposal costs while supplying secondary raw materials to the market (Leidel, 1993; Teixeira, 2001; Tonini; Astrup, 2012), in accordance with the principles of industrial ecology (Giannetti; Almeida, 2006), cleaner production (UNEP, 2013), and eco-efficiency, as established in the Brazilian Association of Technical Standards (ABNT) standard NBR ISO 14045 (ABNT, 2014).

In Brazil, the National Solid Waste Policy (PNRS), established by Law No. 12,305/2010 (Brasil, 2010), is based on the principles of industrial ecology. Its principal objectives include the prevention of waste generation; the reduction, reuse, recycling,

and treatment of solid waste; and the environmentally sound final disposal of rejects. The PNRS represents an important milestone in Brazilian waste management, establishing guidelines for the integrated and sustainable management of solid waste. However, several gaps and challenges in implementing this policy have become evident over the years, requiring critical analysis and the pursuit of innovative solutions (Mont'Alverne; Holanda, 2025).

Industrial waste valorization is associated with the circular economy because it promotes the return of materials to the production cycle and reduces the linear logic of extraction, production, consumption, and disposal of materials. However, this practice must be guided by technical standards, laboratory testing, and risk analysis. ABNT NBR 10004 (ABNT, 2004) classifies solid waste according to its potential risks to the environment and public health, and is therefore an essential reference for any reuse study. Moreover, parameters such as leaching, solubilization, durability, mechanical strength, water absorption, and dimensional stability must be assessed before application at a production scale.

Thus, valorizing industrial waste as a raw material for new products makes a practical contribution in three main dimensions, providing a pragmatic response to the ongoing civilizational crisis and supporting the necessary joint achievement of the 20 SDGs. In the environmental dimension, it reduces landfill disposal, natural resource extraction, and the impacts associated with the production of conventional inputs. In the technological dimension, it fosters the development of new materials, formulations, and production processes (Kniess et al., 2019). In the economic dimension, it can reduce waste disposal costs and expand the availability of alternative raw materials. The incorporation of industrial waste into material production should therefore be understood as a concrete sustainable-innovation strategy.

The circular economy proposes a shift in the logic governing the production and market placement of goods, a change that must occur through continual dialogue among the state, those affected by new policies, and those able to contribute. Studies of this economic conception demonstrate the need for a systemic culture that enables resources to enter production cycles while mitigating waste. This requires ongoing systemic diagnosis to ensure that a technology or new material does not create more problems than the single problem it was intended to solve (Mont'Alverne; Holanda, 2025).

3. SUSTAINABLE INNOVATION

Technological innovation strategies guided by the principles of sustainable development have become increasingly important, given the need to reconcile economic

development, environmental protection, and social responsibility. In this context, innovation is no longer understood solely as a means of increasing productivity; it also encompasses objectives related to reducing natural resource consumption, minimizing waste and emissions, developing more efficient processes, and creating solutions capable of generating environmental and social benefits. Eco-innovation is one of the principal approaches in this field because it integrates innovation, economic performance, and sustainability, thereby contributing to the achievement of the SDGs and the transformation of production systems (Fatma; Haleem, 2023).

This transformation also requires changes in the management and business models adopted by organizations. Incorporating sustainability and circular economy principles into corporate strategies enhances companies' capacity to create value in a more integrated manner, considering not only economic outcomes but also the environmental and social impacts associated with their activities. In this regard, innovation in sustainable business models helps reorganize processes, supplier relationships, resource use, waste generation, and forms of interaction with different stakeholders, thereby strengthening the transition toward more sustainable and resilient production systems (Brenner; Drdla, 2023).

According to the OECD (2015), innovation is a critical factor in developing a more inclusive and sustainable world and "involves the creation and diffusion of new products, processes, and methods." Innovation is not an end in itself; rather, it is the fundamental basis for creating new businesses and jobs and, consequently, for the economic development of nations.

According to the Oslo Manual, innovation is the implementation of a new or significantly improved product (good or service), process, marketing method, or organizational method in business practices, workplace organization, or external relations (OECD, 2005). The innovation process is a key business process associated with renewal and evolution. Innovation can therefore be regarded as an essential activity linked to organizational survival and growth. Each organization must develop its own innovation process based on the particular characteristics of its sector, strategic choices, and culture (Tidd; Bessant, 2018).

Within this context, sustainable management plays an important role and may be characterized as the organization of the entire process of applying innovation to achieve sustainability, waste reduction, social responsibility, and competitive advantage through learning and continuous development, embracing goals and strategies that are fully integrated with the organization's objectives and strategies (Haden; Oyler; Humphreys, 2009).

Organizations are therefore responsible for creating and managing innovative alternatives for products, processes, and resources that are increasingly efficient and effective. In

this context, sustainable innovation emerges and may be conceptualized as the introduction, through production, assimilation, or exploitation, of products, production processes, management methods, or business practices that are new or significantly improved for the organization and generate economic, social, and environmental benefits compared with relevant alternatives (Barbieri et al., 2010).

Sustainable innovation is an alternative pathway for building a new low-carbon economy, aimed at sustainable development and enabling initiatives focused on mitigating and adapting to environmental impacts. Such initiatives must always be supported by a systemic diagnosis that prevents partial solutions from creating new problems, particularly those associated with climate change (Pinsky et al., 2015).

Within the concept of sustainable innovation, waste recycling offers an opportunity to transform a major source of expenditure into a source of revenue or, at a minimum, to reduce disposal expenses. Incorporating waste into production processes lowers costs and creates new business opportunities while reducing raw material extraction and preserving limited natural resources.

4. SUSTAINABILITY IN CONSTRUCTION

The construction industry is essential for economic, social, and environmental development because it directly contributes to the provision of urban infrastructure, job creation, economic dynamism, and improved living conditions. Its activities encompass different stages and segments, including the planning, execution, maintenance, and rehabilitation of works such as buildings, roads, ports, airports, sanitation facilities, foundations, and earthworks. Construction is indispensable to contemporary society because it provides the spaces, systems, and facilities required for the organization of cities and the development of productive activities.

Despite its economic and social relevance, construction is also recognized as one of the activities that exert the greatest pressure on the environment. This impact primarily results from high natural resource consumption, intensive raw material extraction, energy consumption, atmospheric emissions, and substantial waste generation throughout the life cycle of construction work. Morais (2006) noted that a significant share of the inputs used to produce construction materials originates from the extraction of natural deposits. This condition reinforces the need to reconsider traditional patterns of production, consumption, and disposal in the sector.

Accelerated urban growth has intensified this problem. According to Brasileiro and Matos (2015), urbanization has expanded construction activity and consequently

increased both raw material extraction and the generation of CDW. Tang et al. (2020) observed that population growth, economic expansion, and rapid urbanization have aggravated solid waste generation worldwide. Caldas et al. (2015) also drew attention to the high energy consumption of the sector and the associated atmospheric emissions. Thus, construction has a dual character: although it is necessary for urban development, it also has substantial impacts on natural resources, the urban environment, and public health.

The principal environmental problems associated with construction are raw material extraction and waste generation. Natural resource extraction may cause deforestation, landscape alteration, depletion of deposits, air pollution, and ecosystem degradation. Waste generation may result in public expenditure on collection and urban cleaning, contamination of soil and water bodies, obstruction of drainage systems, visual degradation of public spaces, and the creation of conditions favorable to urban pests. Silva et al. (2016) warned that irregular disposal of CDW can cause environmental contamination and foster rats, mosquitoes, and other vectors, thereby compromising public health. These problems demonstrate that inadequate waste management extends beyond environmental dimensions to encompass social, health, and economic concerns.

In this context, and given the challenge of jointly achieving the 20 SDGs, sustainability is indispensable to the construction sector. The main challenges include reducing and optimizing material and energy consumption, decreasing waste generation, preserving the natural environment, and improving the quality of the built environment. Addressing these challenges requires revising traditional concepts in architecture and engineering; adopting solutions that promote rational energy use and renewable sources; managing water efficiently; reducing the use of high-impact materials; and minimizing waste generation during the construction, use, and demolition of buildings.

Therefore, sustainable construction should be understood as an integrated approach that considers every stage of development. According to the Construction Industry Chamber (CIC, 2008), sustainable construction should be conceived and planned to favor environmentally appropriate materials, preferably certified and associated with lower CO_2 emissions; reduce waste generation during construction; comply with technical standards; rationalize energy and water use during construction and operation; and enable materials to be reused at the end of their service life.

The Brazilian Association of Architectural Firms (AsBEA), the Brazilian Council for Sustainable Construction (CBCS), and other institutions have identified principles that guide sustainable construction. These include using local natural conditions, analyzing the surroundings, reducing environmental impacts, ensuring indoor and outdoor environmental quality, sustainably managing construction implementation, adapting to users' present

and future needs, using eco-efficient raw materials, reducing energy and water consumption, reusing and recycling solid waste, introducing technological innovations, and promoting environmental education among those involved in the construction process (CBCS, 2024).

In addition, the Institute for the Development of Ecological Housing (IDHEA, 2013) proposes nine principles for making construction more sustainable: sustainable planning, passive use of natural resources, energy efficiency, water management and conservation, building waste management, indoor air and environmental quality, thermal and acoustic comfort, rational material use, and the use of environmentally appropriate products and technologies. These principles show that sustainability in construction is not limited to material selection but also involves decisions concerning design, execution, operation, maintenance, and the final destination of building components.

Adopting sustainable practices should also be understood as an opportunity for innovation and performance improvement. Leite (2011) observed that sustainability has been incorporated into the sector not only as a conservation measure but also as a means of combating waste, reducing costs, improving processes, innovating, and developing new businesses. Management practices aimed at cost reduction can simultaneously help reduce energy consumption, waste generation, and excessive raw material use.

Furthermore, the construction sector must progress from a linear model based on extraction, production, consumption, and disposal to a more circular logic centered on waste reduction, material reuse, and waste valorization. Barbieri (2012) emphasizes that companies' role in promoting sustainable development encompasses not only respect for the environment but also responsibility for the social, economic, and environmental problems arising from their activities. Sustainability in construction should thus be treated as a strategic guideline capable of integrating environmental preservation, production efficiency, social responsibility, and technological innovation.

In this transition, the valorization of industrial waste and CDW is a concrete alternative for reducing the pressure on natural resources and mitigating the environmental impacts of the sector. Reusing these materials as raw materials for new construction products helps reduce improper disposal, conserve mineral resources, and develop more sustainable technological solutions. Thus, efficient waste management and the incorporation of alternative materials cease to be peripheral actions and become central to the agenda of contemporary construction.

CDW comprises waste from the construction, renovation, repair, and demolition of civil works, as well as waste resulting from site preparation and excavation, commonly known as construction debris, rubble, or demolition material, as defined in National Environment Council (CONAMA) Resolution No. 307/2002 (Brasil, 2002).

Under the PNRS, as with other waste types, the generators bear the primary responsibility for the proper management of CDW. This responsibility may also extend to transport operators and entities responsible for public urban cleaning and solid waste management services.

According to the Brazilian Association for Recycling Construction and Demolition Waste (ABRECON, 2025), CDW generated by individuals and demolition contractors accounts for approximately 46% of the total in Brazil. Construction companies are the other principal generators, accounting for 30% of CDW generated in Brazil, whereas public agencies and paving contractors account for 12% each. On the basis of these proportions, the national total was estimated from the main generators of this waste. Thus, Brazil is estimated to have generated approximately 101 million metric tons of CDW in 2024 (ABREMA, 2025).

At the regional level, Southeast Brazil has the largest share of national CDW generation, accounting for 43.2% of the total. The North contributes the smallest share, corresponding to 7.8% of the national total (ABREMA, 2025).

5. CASE STUDIES AND PRACTICAL EXPERIENCE

5.1. Use of CDW in surface-course formulations for permeable urban pavements

CDW is generated by construction, renovation, demolition, and other infrastructure activities. It comprises concrete, mortar, ceramics, soil, wood, metals, glass, gypsum, and plastics and is commonly disposed of in landfills because of cultural paradigms and the limited market for recycling (Brasileiro; Matos, 2015). CONAMA Resolution No. 307/2002 establishes guidelines for the management of these wastes and classifies them according to their potential for reuse, recycling, or specific disposal. Class A wastes, such as concrete, mortar, bricks, blocks, and earthwork soils, have considerable potential for use as recycled aggregates in paving, nonstructural concrete, mortars, and cement-based products.

The master's thesis entitled "Use of Construction and Demolition Waste (CDW) in Surface-Course Formulations for Permeable Urban Pavements," by Lucas Maia de Souza (Souza, 2022), completed in the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu, investigated the use of CDW as a partial or total substitute for natural aggregates in producing concrete surface courses for permeable urban pavements. This study integrated two major problems in contemporary construction: high CDW generation and increasing urban soil sealing, which contribute to greater surface runoff, flooding, and waterlogging in urbanized areas.

This study began with the recognition that construction is among the sectors that consume the most natural resources and generate the most waste. Urban development intensifies the demand for construction materials, expands raw material extraction, and increases waste from construction, renovation, and demolition. When improperly discarded, this waste aggravates environmental, social, and economic problems, including soil contamination, visual degradation of public areas, landfill occupation, higher public collection expenditure, and public health risks. Simultaneously, urbanization expands impermeable areas, reducing the natural infiltration of water into the soil and intensifying urban drainage problems.

Against this background, the overall objective of this study was to develop and characterize concrete surface courses for permeable pavements using recycled CDW aggregates as an alternative raw material. This study also sought to use patent information to identify related products, processes, and technological pathways; determine the chemical and mineralogical characteristics of recycled aggregates; apply mixture design to assess the influence of cement, recycled aggregate, and natural aggregate proportions; obtain regression models and response surfaces; compare the technical performance of the formulations; and preliminarily assess environmental, social, and economic aspects of the proposal.

Theoretically, this study was grounded in the concepts of sustainability, circular economy, cleaner production, reverse logistics, and life-cycle assessment. CDW valorization is a strategy aligned with the PNRS (Brasil, 2010), particularly because it supports the reuse and recycling of materials that are often improperly discarded. It is also related to the need for the joint achievement of the SDGs of the 2030 Agenda (ONU, 2015), primarily through its contribution to more sustainable cities, infrastructure innovation, responsible consumption, and reduced environmental impacts from the construction sector.

A distinctive methodological feature of this research is its use of patent information as a source for technology prospecting. The author consulted patent databases to identify trends, technical solutions, and application pathways related to permeable pavements containing waste. This stage provided an understanding of how the subject has been explored technologically and informed the definition of the experimental process. Using patents as an information source broadens the study's contribution by bringing academic research closer to applied innovation and solutions with technology-transfer potential.

Three principal components were used in the experimental stage: cement, natural aggregate, and recycled aggregate derived from the CDW. The surface course mixes were defined using an extreme-vertices mixture design with Minitab Statistical Software, version 20.3.0.0. The design produced 11 formulations within the following limits: cement (CI), 14.43%–27.25%; recycled aggregate (CDW), 3.75%–85.57%; and natural aggregate

(AGRN), 0%–72.52%. This strategy enabled the systematic evaluation of the influence of each component on the properties of pervious concrete while reducing the dependence on empirical trial-and-error formulations.

The surface course materials were characterized in the fresh state through density measurements and in the hardened state through tests of water absorption, void content, density, flexural tensile strength, and permeability coefficient. These parameters are fundamental for permeable pavements because the material must reconcile infiltration capacity with sufficient mechanical strength for the anticipated traffic. Therefore, this study simultaneously assessed the hydraulic and mechanical performance of the formulations, which is a necessary condition for verifying the practical applicability of the developed product.

The results showed that increasing the recycled aggregate content increased the water absorption, void content, and permeability coefficient. This behavior is consistent with the greater porosity generally associated with recycled CDW aggregates used in this study. However, CDW use also reduced the mechanical strength of the surface courses, particularly flexural tensile strength. This study identified a trade-off between hydraulic and mechanical performance: higher CDW content improved permeability but may impair material strength unless the mixture is properly controlled.

Regarding normative requirements, the master's thesis indicates that nearly all formulations met the minimum strength specified in NBR 16416:2015 (ABNT, 2015) for permeable surface courses intended for pedestrian traffic, namely, 1.0 MPa. Only formulation F7 (CI 14.43%, CDW 85.57%, and AGRN 0.00%) failed to meet this criterion. For light-traffic applications, which require a minimum strength of 2.0 MPa, only formulation F9 (CI 27.25%, CDW 3.75%, and AGRN 69.00%) met the requirement. This result demonstrates that CDW can be used in permeable surface courses, but its application depends on an appropriate percentage, particularly when the product is intended for higher mechanical loads.

The preliminary economic analysis indicated that the recycled aggregates were economically viable. This finding is relevant because using CDW in permeable pavements can reduce the dependence on natural aggregates, lower waste disposal costs, extend landfill service life, and create uses for recycled materials. Urban paving is particularly promising because it consumes large volumes of material, enabling substantial quantities of CDW to be absorbed.

The principal academic contribution of this study lies in the integration of technology prospecting, experimental mixture design, and performance assessment of pervious concrete containing CDW. This demonstrates that statistical tools can be used to simulate formulations, identify application limits, and understand the influence of components on

composite properties. This procedure accelerates material development, enhances control, and is technically grounded, thereby bridging experimental research and practical applications in construction.

From a practical perspective, this study demonstrates that CDW can be used to produce permeable surface courses for urban paving, particularly for pedestrian-traffic applications, provided that the proportions of cement, recycled aggregate, and natural aggregate are properly designed. The proposed solution simultaneously contributes to waste management and sustainable urban drainage by transforming problematic waste into a raw material for a product capable of promoting water infiltration into the soil and reducing surface runoff.

Therefore, this thesis makes a relevant contribution to sustainable construction by proposing a CDW valorization pathway for permeable pavements. This confirms that recycled aggregates improve permeability-related properties, although high contents reduce mechanical strength. Consequently, the technical feasibility depends on the balance between porosity, permeability, and strength. This study shows that incorporating waste into construction materials must be supported by appropriate characterization, experimental design, quality control, and normative assessment, thereby establishing the systemic diagnosis required to prevent the adoption of a solution considered innovative from introducing unintended consequences that could undermine the benefits initially intended.

Thus, this study offers a concrete alternative for reducing the environmental impacts of construction, expanding the use of recycled materials, and contributing to more sustainable and resilient cities.

5.2. Production and characterization of rendering mortars made with CDW as recycled aggregate

The master's thesis "Production and Characterization of Rendering Mortars Made with Construction and Demolition Waste (CDW) as Recycled Aggregate," by Daniela Aparecida Dutra de Lima (Lima, 2022), completed in the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu, investigated the possibility of using CDW as recycled aggregate in rendering mortars. This study addresses a recurrent problem in construction: despite its economic and social relevance, the sector is a major consumer of natural raw materials and a principal generator of solid waste, creating environmental, technical, and economic management challenges.

This study lies within the field of sustainability applied to construction, with an emphasis on waste valorization. The author notes that CDW may comprise ceramics, mortar,

concrete, debris from precast elements, and other components that can be recycled and reintroduced into new construction products. Thus, reusing CDW in rendering mortars is presented as an alternative for reducing irregular disposal, decreasing natural aggregate extraction, extending landfill service life, and contributing to more sustainable practices throughout the construction value chain.

The overall objective of this thesis was to produce and characterize rendering mortars made with CDW as recycled aggregate. To achieve this objective, the study established specific objectives concerning technology prospecting through patent databases; the use of mixture design to determine component proportions; characterization of the recycled aggregate and mortars; comparison with mortars containing natural aggregate; assessment of technical and economic feasibility; and the proposal of alternatives aligned with the challenge of jointly achieving the SDGs of the 2030 Agenda (ONU, 2015).

This study was justified by the fact that, although CDW is governed by specific legislation, it continues to be frequently discarded improperly, causing environmental, social, physical, and economic impacts. Irregular disposal may result in standing water, proliferation of insects and rodents, environmental contamination, and degradation of urban quality. Recycling, in turn, helps extend landfill service life, reduces irregular disposal, decreases the consumption of natural raw materials, and mitigates emissions associated with the extraction and transportation of construction materials.

This thesis addresses sustainability, environmental management, waste management, sustainability in construction, CDW, mortars, rendering mortars, and patent information. The author discusses CONAMA Resolution No. 307/2002, which classifies CDW and establishes management guidelines, as well as the PNRS, which prioritizes waste prevention, reduction, reuse, recycling, treatment, and environmentally sound final disposal of waste. This framework reinforces the relevance of the study by positioning CDW use as a solution compatible with public policies for environmental management and the circular economy.

A distinctive methodological feature of this research is its use of patent information for technology prospecting. This study analyzed scientific journal databases and patent documents to define the technological pathway for mortar production. This approach identified processes, products, and technologies already described in patents, reducing uncertainty and bringing academic work closer to solutions with practical application potential. Patents are relevant sources of technological information because they describe inventions, functions, and development pathways that do not always appear in conventional scientific publications.

The experimental methodology was organized into the following stages: literature review, patent information survey, selection and characterization of raw materials, formu-

lation study through mixture design, mortar production, characterization in the fresh and hardened states, and preliminary economic feasibility analysis. The methodological flowchart of this study presents a logical sequence beginning with scientific and technological research, proceeding to CDW collection and physical, chemical, and mineralogical characterization of the raw materials, and culminating in mortar production and assessment.

An extreme-vertices mixture design was used to formulate the mortars using Minitab Statistical Software. The design generated 13 formulations comprising three principal components: cement, natural aggregates, and recycled aggregates. The adopted limits were as follows: cement (CI), 14.90%–33.33%; natural aggregate (AGRN), 0%–72.00%; and recycled aggregate (AGRR), 6.67%–75.00%. Hydrated lime was maintained as a fixed component because including it as a variable would excessively increase the number of formulations.

The mortars were characterized in the fresh state by density and consistency index testing, according to ABNT NBR 15116:2021 (ABNT, 2021). In the hardened state, the assessed properties included capillary water absorption, water absorption by immersion, void content, ultrasonic pulse velocity, tensile bond strength, flexural tensile strength, and compressive strength of the specimens. These tests enabled the assessment of not only the physical behavior of the mortars but also their mechanical performance and suitability as rendering materials.

The results indicated that incorporating recycled aggregates increased the water absorption and void content of the mortars. This behavior is consistent with the nature of CDW, which tends to exhibit greater porosity and absorption than natural aggregates. The study nevertheless found that recycled aggregates also increased compressive strength, flexural tensile strength, and bond strength. This is important because it shows that when properly processed and proportioned, CDW does not merely act as a lower-value substitute but can positively affect the fundamental properties of rendering mortars.

Statistical analysis was a significant contribution to the study. Mixture design enabled the generation of equations for each assessed property, permitting the estimation of mortar behavior from the proportions of cement, natural aggregate, and recycled aggregate. Therefore, the research was not limited to direct comparisons among mixes; it proposed models capable of simulating compositions and identifying opportunities and constraints for use. Mixture design also enabled the production of residual and contour plots to interpret the influence of the components on the formulation properties.

In normative terms, this thesis reports that all formulations complied with ABNT NBR 13281:2005 (ABNT, 2005), superseded by ABNT NBR 13281-1:2023 (ABNT, 2023), regarding compressive and flexural tensile strengths. For tensile bond strength, only formulations F1 (CI 19.35%, AGRN 53.84%, AGRR 26.81%) and F4 (CI 14.90%, AGRN

72.00%, AGRR 13.10%) fell below the values specified in the standard. Formulations such as F5 (CI 33.33%, AGRN 0%, AGRR 66.67%), F6 (CI 23.80%, AGRN 35.68%, AGRR 40.52%), F7 (CI 25.0%, AGRN 0%, AGRR 75.0%), and F8 (CI 22.56%, AGRN 53.84%, AGRR 23.59%) were identified as having greater use potential, indicating composition regions in which CDW can achieve satisfactory technical performance.

The preliminary economic analysis showed that recycled aggregates were more economically advantageous than natural aggregates, whereas industrialized mortars were less economically feasible. This finding reinforces the practical contribution of this study by demonstrating that partially or fully replacing natural aggregates with recycled aggregates can be advantageous not only environmentally but also economically, provided that the performance and quality-control criteria are met.

The study's social contribution concerns its potential to reduce irregular CDW disposal, decrease urban and environmental impacts, and promote a more technically appropriate destination for waste generated by the construction sector. The academic contribution of this study lies in the combination of patent information, experimental mixture design, and characterization of mortars containing recycled aggregates. The technological contribution of this study is the demonstration that CDW can be incorporated into rendering mortars with performance compatible with normative requirements and practical application potential in construction.

This thesis demonstrates the technical and economic feasibility of using CDW as recycled aggregates in rendering mortars. Although recycled aggregates increase porosity-related properties, such as water absorption and void content, they can also improve important mechanical properties, including compressive strength, flexural tensile strength, and bond strength. Therefore, this study confirms that CDW can be treated as a valuable alternative raw material, provided that it is properly characterized, processed, and proportioned. This further shows that waste valorization in construction requires the integration of sustainability, technological innovation, experimental design, and performance assessment.

5.3. Production and characterization of ceramic materials using sewage-treatment sludge as an alternative raw material

The master’s thesis “Production and Characterization of Ceramic Materials Using Sewage-Treatment Sludge as an Alternative Raw Material,” developed by Lucas José Nasraui in the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu (Nasraui, 2023), investigated the technical feasibility of incorporating sewage sludge from wastewater treatment plants (WWTPs) into ceramic materials. This study

lies at the interface of civil engineering, sanitation, materials technology, and sustainability, with the need for environmentally appropriate alternatives for sewage sludge disposal as its central problem.

Waste streams of known origin include those generated during sewage treatment at a WWTP. When it contains no industrial waste, sewage is composed of 99.87% water, 0.04% settleable solids, 0.02% nonsettleable solids, and 0.07% dissolved substances (Nuvolari et al., 2011). WWTPs were created to reduce the impacts caused by wastewater discharge, minimizing the effects of returning these waters to the environment (Nasraui, 2023).

The National Basic Sanitation Information System (SINISA) is the principal official structure of the Brazilian Federal Government for collecting, organizing, and disseminating information on basic sanitation services. The system succeeded the National Sanitation Information System (SNIS), whose final data collection occurred in 2023. SINISA 2025 recorded participation by 2,749 municipalities, corresponding to 49.4% of all Brazilian municipalities (Brasil, 2025). The results show that access to sewage networks is far from universal. In 2024, 62.3% of the total population of the participating municipalities, approximately 117.3 million people, was served by a sewage collection network. Considering only the urban population, the coverage reached 68.4%, or approximately 116.4 million people. The situation was substantially different in rural areas: only 4.8% of the rural population, approximately 900,000 people, was served by a sewage collection network.

Another fundamental aspect is the distinction between sewage collection and treatment. According to SINISA 2025, with 2024 as the reference year, the volume of sewage collected corresponded to 61.8% of the volume of water consumed. In turn, the volume of treated sewage corresponded to 51.8% of the volume of water consumed. When treatment is considered relative to the sewage collected, the indicator reached 85.2%. These percentages have different calculation bases, since the indicator for treatment of collected sewage also incorporates volumes of sewage imported and exported between systems. Therefore, the values cannot be obtained simply as the ratio between the percentages of treated and collected sewage relative to water consumed. This distinction shows that existing treatment capacity does not necessarily mean that all the sewage produced is collected and conveyed for treatment.

Waste recycling and reuse in production processes are aligned with the targets of the SDGs of the 2030 Agenda and contribute to the broader scope of jointly achieving 20 SDGs (Cabral; Galvão, 2025). The indicators are related to SDG 6 (Clean Water and Sanitation), whose Target 6.2 seeks access to adequate and equitable sanitation and hygiene, and whose Target 6.3 concerns improving water quality by reducing pollution and the discharge of untreated wastewater. Depending on the approach adopted, the effects

of sanitation may also be related to SDG 3 (Good Health and Well-Being), SDG 10 (Reduced Inequalities), SDG 11 (Sustainable Cities and Communities), and the SDGs associated with protecting natural resources. Reusing sewage treatment sludge also has a notable relationship with SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production).

This study recognizes sewage sludge as a waste stream with complex disposal requirements, traditionally destined for sanitary landfills, agricultural applications, or incineration. Although agricultural application is a recurrent alternative, it requires strict control of the chemical and sanitary composition of the material, particularly because of organic matter, nutrients, salts, and possible contaminants. In this context, the thesis engages with the PNRS, which prioritizes waste prevention, reduction, reuse, recycling, and treatment before environmentally sound final disposal (Brasil, 2010). It is also related to the Legal Framework for Basic Sanitation, which establishes targets for universal access to drinking water and sewage collection and treatment by 2033 (Brasil, 2020). The proposal to use sludge as an alternative raw material in ceramics represents a possibility for waste valorization aligned with the circular economy and reduction of environmental impacts.

The overall objective of this study was to investigate the production and characterization of ceramic materials using domestic sewage treatment sludge as an alternative raw material. To achieve this objective, the master's thesis was organized into four interdependent studies: a systematic literature review of sludge use as a construction material; physicochemical characterization of WWTP sludge; definition of the ceramic formulation and processing methodology through experimental design; and characterization of the ceramic materials produced. This methodological organization integrated a theoretical survey, raw material characterization, composition planning, and assessment of the technological properties of the test specimens.

The sludge collected at the Várzea Paulista WWTP (São Paulo), operated by SABESP (the São Paulo state water and sanitation utility), underwent physicochemical and mineralogical characterization. The parameters considered included moisture content, loss on ignition, pH, electrical conductivity, sodium content, X-ray fluorescence, X-ray diffraction, and thermogravimetric analysis. The results indicated a mineralogical composition compatible with clay materials used in the ceramics industry, with a predominance of silica, alumina, and hematite, and the presence of kaolinite. This compositional compatibility provides a technical basis for partially incorporating sludge into ceramic bodies, provided that the substitution limits and appropriate processing parameters are observed.

An experimental mixture design was adopted for this study. The compositions were defined using three principal raw materials: sewage sludge, illitic clay, and kaolinitic clay.

The adopted limits were 5%–15% sewage sludge, 10%–20% illitic clay, and 75%–85% kaolinitic clay. Ceramic processing was performed via the dry route, with sintering at 1100 °C. This stage was central to transforming the environmental problem of waste into a technological problem of ceramic body formulation, making it possible to assess how the proportions of each component influenced the final material properties.

The specimens were characterized through technological properties fundamental to ceramic materials, including water absorption, apparent porosity, linear shrinkage, dry and sintered bulk density, and flexural strength modulus in the dry and sintered conditions. The resulting data were statistically analyzed using Minitab to generate fitted models for each property as a function of the ceramic body composition. This modeling enabled the identification of trends, comparison of formulations, and determination of an optimal composition by superimposing response surfaces.

The results showed that it was possible to obtain materials classified as semiporous tiles, with water absorption between 6% and 10% and a minimum sintered flexural strength modulus of 18 MPa. These values indicate the initial technical feasibility of using sewage sludge in ceramic compositions while complying with the normative limits applicable to ceramic tiles. The thesis also found that the mathematical models exhibited a good fit for most assessed properties, although flexural strength behavior was less adequately explained by ceramic-body composition alone. The optimal mixture comprised 76.4% kaolinitic clay, 18.4% illitic clay, and 5.2% sewage sludge.

From a scientific and technological standpoint, this study demonstrates that sewage sludge can be treated not only as an environmental liability but also as a potential input for the ceramics sector. This study also makes a methodological contribution by combining systematic review, physicochemical characterization, mixture design, and statistical modeling. This integration strengthens the reliability of the analysis because the material formulations did not arise from isolated empirical trial and error but from a planned and technically grounded experimental procedure.

Finally, this thesis makes a direct contribution to the 2030 Agenda, particularly SDGs 6, 9, and 12. SDG 6 is addressed through the relationship with sanitation and WWTP waste management; SDG 9 appears in the dimensions of industrial innovation and technological development; and SDG 12 is supported by the logic of responsible consumption and production through the proposed reinsertion of waste into the production chain. Therefore, this study is academically, environmentally, and practically relevant because it offers a technically investigated alternative for reducing improper sewage sludge disposal while expanding the use of alternative raw materials in the ceramics industry.

6. BENEFITS AND APPLICATION CHALLENGES

Valorizing industrial waste as raw material for construction materials provides relevant environmental, economic, and technological benefits, particularly in a sector characterized by high consumption of natural resources, energy, and mineral inputs. The construction sector depends heavily on aggregates, clays, limestone, sand, water, and cementitious materials, while generating large volumes of waste during production, transportation, execution, maintenance, and demolition. In this context, incorporating industrial waste into concrete, mortars, ceramics, pavements, blocks, and cement-based products is a concrete alternative for reducing environmental impacts and improving resource-use efficiency.

From an environmental perspective, the principal benefit is the reduction in natural raw material extraction and waste disposal in landfills or inappropriate areas. Beyond reducing direct environmental impacts, waste valorization contributes to the transition from a linear production model to a circular economy logic. Instead of following the conventional flow of extraction, manufacture, use, and disposal, waste is returned to the production cycle as secondary raw materials. This approach is particularly important in construction because the sector can absorb materials on a large scale (John, 2000).

The economic benefits are also significant in this regard. For waste-generating industries, valorization can reduce waste transportation, treatment, and disposal costs. The construction value chain can expand the supply of alternative raw materials, reduce dependence on natural inputs, and favor lower-cost production solutions, particularly in high-volume applications such as paving, blocks, mortars, ceramics, and nonstructural concrete. In some cases, waste can also improve specific material properties and add value to products. For example, recycled CDW aggregates can reduce the demand for natural aggregates and generate new economic chains associated with the collection, sorting, processing, certification, and marketing of recycled materials.

In the technological domain, waste valorization drives innovation in materials, processes, and control methods. Incorporating waste requires studies on chemical composition, particle size distribution, reactivity, leaching, solubilization, mechanical strength, durability, water absorption, and dimensional stability. These requirements have stimulated the development of more efficient formulations, proportioning methods, processing operations, separation techniques, and quality control systems. In ceramic materials, for example, waste rich in silica, alumina, iron oxides, or carbonates may act as fluxes, fuels, or property modifiers.

Recent recycling technologies also increase the practical feasibility of waste valorization. For CDW, recent studies have highlighted advances in automated sorting,

sensor-based separation, contaminant control, digital traceability, and decision-support tools. Bonifazi et al. (2025) emphasized that the main challenges in recycling CDW involve compositional heterogeneity, the presence of contaminants, and the need for technologies capable of improving the quality of recycled materials.

Therefore, the environmental, economic, and technological benefits of industrial waste valorization are interrelated. Reducing environmental impact depends on technical feasibility; economic feasibility depends on scale, logistics, and performance; and technological advancement depends on characterization, control, and experimental validation. Industrial waste valorization should consequently be understood not merely as a disposal solution but also as a sustainable innovation strategy for the construction sector. When undertaken with technical and normative rigor, it helps reduce pressure on natural resources, generate new products, lower operating costs, and strengthen circular and responsible production models.

The valorization of industrial waste as a raw material for construction materials has considerable environmental, economic, and technological potential; however, its application is not free from limitations. The main challenges include (a) variability in waste composition; (b) environmental and health risks; (c) technical performance of materials; (d) logistics for collection, segregation, transportation, and processing; (e) normative barriers and market acceptance; (f) economic risks; and (g) life-cycle assessment.

In the construction sector, these challenges are even more relevant because the sector already exhibits high consumption of materials, energy, and natural resources, in addition to substantial waste generation. According to Brazil's Ministry of the Environment (Brasil, [2012?]), the principal challenges facing the construction sector include reducing and optimizing material and energy consumption, reducing waste generation, preserving the natural environment, and improving the quality of the built environment. In the face of the current civilizational crisis, industrial waste valorization must be understood as part of a broader sustainability strategy rather than an isolated solution.

Application challenges do not preclude industrial waste valorization but indicate the need for technical rigor, normative controls, and multidimensional assessments. Incorporating these materials into construction must consider performance, environmental safety, economic feasibility, supply regularity, market acceptance, and life-cycle impacts. When these aspects are neglected, recycling can generate unsafe, unstable, or environmentally inappropriate products, reinforcing the premise that the absence of a systemic diagnosis may cause a prematurely adopted technology to create more problems than the single problem it solves. When properly controlled, industrial waste can become high-value secondary raw materials, contributing to a construction sector that is more efficient, circular, and sustainable.

7. FINAL CONSIDERATIONS

Valorization of industrial waste as a raw material for construction materials is a relevant strategy for contemporary construction, particularly given the need to reduce natural resource consumption, minimize improper waste disposal, improve production process efficiency, and contribute to infrastructure decarbonization. Recent international reports indicate that civil engineering plays a strategic role in the transition toward infrastructure systems that are more resilient, efficient, and adapted to climate change (ICE, 2025).

In the face of the ongoing civilizational crisis, marked by social inequality and climate emergency, such valorization represents an important pragmatic contribution by engineering. This chapter has shown that waste such as CDW, domestic sewage-treatment sludge, and other byproducts can cease to be treated solely as environmental liabilities and instead form part of new technological pathways for producing mortars, concrete, pavements, ceramic tiles, and other building components.

The practical experiences presented, developed within the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu, demonstrate that incorporating waste into construction materials requires a technical, experimental, normative, and performance-oriented approach throughout the life cycle of materials and construction systems. Studies on CDW in rendering mortars and permeable pavements indicate that CDW can replace natural aggregates in certain formulations, helping reduce mineral extraction and providing a more appropriate destination for waste generated by the construction chain itself. Similarly, the study of sewage-treatment sludge in ceramic materials demonstrates the possibility of incorporating sanitation waste into higher-value production processes, provided that the composition, processing, and performance limits are respected.

These findings reinforce the notion that waste valorization cannot be understood as a simple raw material substitution. It involves physicochemical, mineralogical, particle size, and environmental characterization, as well as experimental design, statistical modeling, performance testing, and economic feasibility assessment. Tools such as mixture design and patent-database prospecting have proven useful for reducing empiricism, guiding formulations, identifying technological pathways, and bringing academic research closer to practical application in the production sector.

The environmental, economic, and technological benefits of waste valorization are interrelated. Reducing landfill disposal, conserving natural resources, and mitigating environmental impacts depend on the technical feasibility of the produced materials. Likewise, economic feasibility depends on the regular availability of waste and on collection, transportation, processing, and quality control costs. Therefore, waste use in construc-

tion must be assessed systemically, considering performance, safety, durability, standardization, market acceptance, and life-cycle impacts.

This perspective aligns with contemporary discussions of resilient and sustainable infrastructure, in which engineering acts in an integrated manner across resource management, emissions reduction, climate adaptation, and the performance of built assets. Such a systemic diagnosis is fundamental to ensuring that a technology is not based on a merely partial perspective, thereby preventing a solution initially presented as innovative from producing adverse effects or creating new problems over the course of its application.

The identified limitations do not preclude waste application but indicate the need for rigorous criteria to be established. Compositional variability, contaminants, material heterogeneity, normative requirements, and the risk of performance loss must be controlled. Therefore, industrial waste valorization should be regarded as a pathway for sustainable innovation rather than merely an alternative form of disposal.

In conclusion, incorporating industrial waste and CDW into construction materials makes a concrete contribution to the circular economy, technological innovation, and sustainability of the built environment. The studies analyzed demonstrate the technical and economic potential for expanding the use of these materials, provided that their application is guided by appropriate characterization, experimental validation, normative control, and performance assessment. Waste valorization is thus consolidating its position as a strategic agenda for contemporary civil engineering by integrating technological innovation, the circular economy, climate mitigation, and infrastructure resilience in line with global sustainability challenges and the transition toward low-carbon cities and construction systems, aligned with the 2030 Agenda.

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CHAPTER 8

Natural solid waste aggregates in construction: formation of high-performance composites

Rodrigo Teixeira Bento, Wellington Augusto Lopes da Silva, Lucas Maia de Souza, Mostafa Galal Abdelfattah Mohamed Aboelkheir, Fernando Gabriel Benitez Jara

1. CLASSIFICATION AND CHARACTERIZATION OF NATURAL SOLID WASTE AGGREGATES

1.1. Construction and demolition waste (CDW)

One of the challenges of modern times is to enable sustainable development, which requires the rational management of finite inputs so that present development does not compromise the integrity of ecosystems or the security of future generations (WCED, 1987; Souza et al., 2024).

Natural resources are finite and the environment does not have the capacity to absorb the amount of waste generated. The construction industry ranks among the economic sectors with the highest consumption of natural resources and, simultaneously, the highest generation of solid waste worldwide. Recent estimates indicate that the construction industry accounts for approximately 30%–40% of all solid waste produced globally, exerting significant pressure on landfills, mineral extraction areas, and water bodies (Tao et al., 2025).

In Brazil, the situation is particularly concerning. According to the Brazilian Association of Waste and Environment (ABREMA, 2025), whose data refer to 2024, the generation of construction and demolition waste (CDW) reached 100.8 million metric tons, exceeding municipal solid waste, which totaled 81.6 million metric tons. These figures underscore the predominance of CDW and the need for efficient strategies for reusing these materials.

In parallel, the growing demand for conventional aggregates such as sand, crushed stone, and river gravel intensifies the extraction of minerals from natural deposits, a process frequently associated with impacts such as river siltation, removal of riparian vegetation, and particulate emissions (Kępniak; Chylinski; Woyciechowski, 2025). The relative scarcity and the progressive rise in the cost of these inputs have stimulated the investigation of technically equivalent alternatives, with emphasis on aggregates derived from natural solid waste.

In this context, the scientific community has made progress in the characterization and use of two major groups of materials: (i) recycled aggregates of mineral origin, obtained by the mechanical processing of concrete, masonry, and other construction waste; and (ii) aggregates and fibrous reinforcements of plant origin, derived from agro-industrial byproducts such as sugarcane bagasse, rice husk, bamboo, sisal, jute, and coconut (Soldati; Bacciocchi; Tarantino, 2024; Zhang et al., 2025), as shown in Figure 1. Both groups have proven potential to act as functional components of cementitious composites, provided that their specific physicochemical characteristics are properly addressed during mix design.

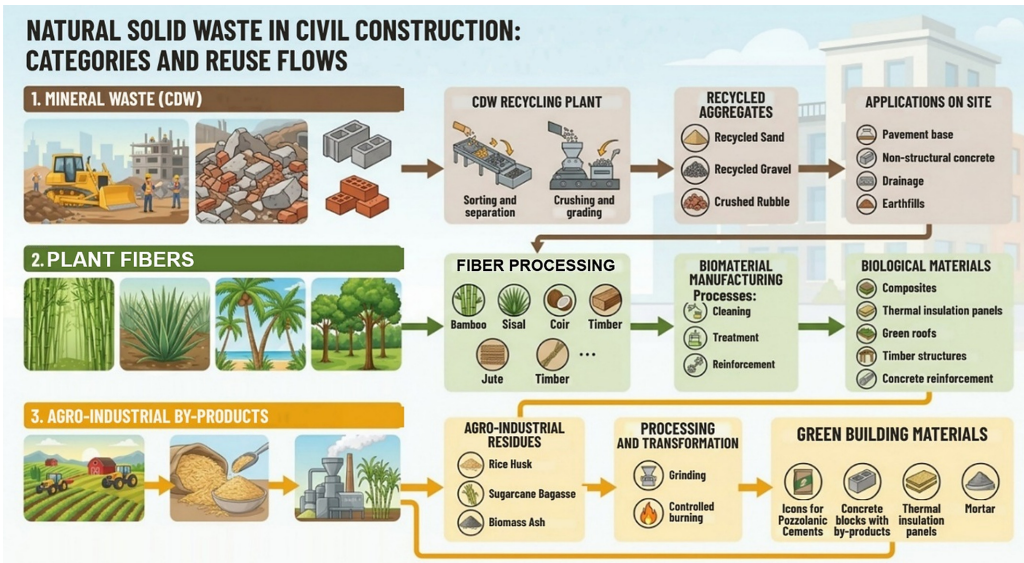


Figure 1 – Schematic diagram of the categories of natural solid waste used in construction: mineral waste (CDW), plant fibers and agro-industrial byproducts, indicating the reuse flows.

CDW constitutes the largest and most extensively studied class of reusable solid waste in the construction industry. Its heterogeneous composition predominantly includes fragments of hardened concrete, mortar, ceramic bricks, and masonry elements and, in small-

er proportions, wood, gypsum, and polymeric materials (Zhang et al., 2025). Resolution No. 307/2002 of the National Environment Council (CONAMA) and its subsequent updates establish the guidelines for the management and recycling of this waste in Brazil, classifying it into four classes (A, B, C, and D) according to its reuse potential (Brasil, 2002).

For use as aggregate in concretes and mortars, Class A CDW (fragments of concrete, mortar, bricks, and ceramic blocks) is crushed, screened, and graded in accordance with ABNT NBR 15116:2021, issued by the Brazilian Association of Technical Standards (ABNT), which regulates recycled aggregates for use in Portland cement mortars and concretes (ABNT, 2021a). The standard distinguishes two main categories: recycled concrete aggregate (RCA), with a minimum content of 90% concrete fragments, and mixed recycled aggregate (MRA), with a more heterogeneous composition.

From a physical standpoint, RCAs differ from natural aggregates in the presence of a layer of residual mortar adhered to the surface of the grains, a phenomenon that increases water absorption (typically between 3.5% and 12%), reduces the apparent specific gravity, and increases total porosity (Dafedar et al., 2024). These characteristics directly affect the interfacial transition zone (ITZ) between the aggregate and the new cement paste and represent the main factor limiting the mechanical performance of recycled aggregate concretes (Kępniak; Chylinski; Woyciechowski, 2025). Table 1 summarizes the main physical properties of natural and recycled aggregates used in concrete production.

The physical and mechanical properties of aggregates play a crucial role in the behavior of concrete in both the fresh and the hardened state. The data in Table 1 show clear differences between the behavior of natural aggregates and that of RCAs.

RCAs invariably exhibit a lower specific gravity than natural aggregates. This difference stems from the physical composition of the particles. Unlike natural aggregate, which is produced by crushing sound, dense rock, recycled aggregate is a two-phase material consisting of a core (a fragment of the original aggregate) and adhered mortar (the remnant of the cement matrix of the original structure that remains bonded to the aggregate after crushing) (Etxeberria et al., 2007).

Since mortar tends to be more porous and less dense than rock (owing to internal voids and the capillary network of the cement gel), it reduces the average density of the particle as a whole. The higher the content of mortar adhered to the RCA, the lower its specific gravity and the greater its water absorption capacity. Studies point to the need to adjust and reassess the water/cement (w/c) ratio, since the immediate absorption of part of the mixing water by the pores of the aggregate ultimately reduces the effective w/c ratio at the paste–aggregate interface. If not compensated for by pre-saturation or by the

addition of compensating water, this phenomenon may severely compromise the workability of the concrete and alter the mechanical properties of the cementitious matrix (Etxeberria et al., 2007; Tavares; Kazmierczak, 2016; Fernandes; Melo, 2020; Kruger et al., 2020; Souza et al., 2022).

Table 1 – Comparison of the physical properties of natural and recycled concrete aggregates

Property	Natural coarse aggregate (limestone gravel)	Natural fine aggregate (sand)	RCA coarse	RCA fine	Reference standard
True specific gravity ($g.cm^{-3}$)	2.65 – 2.80	2.60 – 2.65	2.20 – 2.50	2.10 – 2.45	ABNT NBR 15116:2021
Apparent specific gravity ($g.cm^{-3}$)	2.55 – 2.70	2.50 – 2.60	2.00 – 2.35	1.90 – 2.25	ABNT NBR 16917:2021
Water absorption (%)	0.5 – 1.5	0.3 – 1.0	3.5 – 8.0	5.0 – 12.0	ABNT NBR 16916:2021
Modulus of elasticity (GPa)	60 – 80	–	20 – 40	15 – 35	ASTM C469
Shape index	1.0 – 1.3	–	1.4 – 2.1	1.3 – 1.9	ABNT NBR 7809:2019
Capillary absorption coefficient ($g.cm^{-2}.min^{-1/2}$)	0.02 – 0.06	–	0.08 – 0.18	0.12 – 0.25	EN 1925:1999
pH of the immersion water	7.0 – 8.0	6.5 – 7.5	10.5 – 12.5	11.0 – 13.0	–

Source: Souza et al., 2022; Dafedar et al., 2024; Soldati; Bacciocchi; Tarantino, 2024; Kępniak; Chylinski; Woyciechowski, 2025; Zhang et al., 2025. Test methods: ABNT, 2019b, 2021a, 2021b, 2021c; CEN, 1999.

With regard to morphological characteristics, the shape index of the recycled aggregates proved to be higher than that of the natural aggregates, reflecting the greater geometric irregularity resulting from the crushing of the residual concrete. Higher shape index values imply a greater specific surface area and greater internal friction. This morphological characteristic, combined with the high absorption, is one of the main factors that reduce the workability of concretes produced by replacing natural aggregates with recycled ones (Brito; Saikia, 2013).

The pH results obtained in the studies for RCA (10.5 to 13.0) confirm the presence of cement hydration products; the high alkalinity reflects the portlandite ($Ca(OH)_2$) preserved in the adhered mortar (Kępniak; Chylinski; Woyciechowski, 2025). This characteristic gives the recycled aggregate an alkaline character that, unlike inert natural ag-

gregates, may help maintain the alkalinity of the concrete pore solution, protecting the reinforcement against carbonation-induced depassivation (Leemann; Loser, 2019).

The physical, chemical, and morphological characterization of recycled aggregates is what allows them to be treated as an engineering input rather than as waste. The interaction between the two-phase nature of RCA, its high absorption capacity, and its alkaline character should be interpreted not merely as a technical limitation but as a set of variables that define its most suitable application, whether in new cementitious composites, pavement layers, infrastructure works, or drainage systems. The characteristics described in this section provide the basis for the technical management of the material and for meeting design and durability requirements.

1.2. Plant fibers and aggregates

Unlike mineral aggregates, which are of geological origin and essentially inert, the second major group of natural solid waste of structural interest comprises fibers and aggregates of plant origin.

The shift toward the use of these materials in construction and materials science is driven by the search for low-carbon technologies, since plant fibers are renewable, biodegradable resources that act as CO_2 sinks during their growth cycle (Pacheco-Torgal; Jalali, 2011). Technically, these aggregates are classified as complex natural composite materials with a hierarchical cellular structure that confers low density and insulating properties rarely found in conventional aggregates. Morphologically, these fibers are classified into (Figure 2): (a) bast fibers, such as jute, ramie, hemp, and bamboo; (b) leaf fibers, such as sisal and agave; and (c) fruit/seed fibers, such as coconut and cotton (Ullah et al., 2024).

In terms of chemical composition, plant fibers consist essentially of cellulose (40%–75%), hemicellulose (20%–35%), and lignin (5%–25%). Cellulose, composed of pyranose rings joined by hydrogen bonds, is organized into microfibrils of variable crystallinity. As the primary component, cellulose—through its content and crystallinity—is chiefly responsible for the stiffness and mechanical strength of the fiber (Mehmood et al., 2025). The modulus of elasticity of the fiber may range from 5 GPa (coconut fibers) to 13 GPa (treated sisal), while the tensile strength varies between 200 and 1,000 MPa, depending on the species and the treatment (Jamshaid et al., 2023).

Within this lignocellulosic complex, hemicellulose acts as a branched, amorphous, and highly reactive polymer that is readily soluble in alkaline media. Lignin, in turn, functions as a natural hydrophobic adhesive that binds cellulose to hemicellulose, conferring structural stiffness on the assembly. Whereas cellulose is stable in alkaline solutions,

hemicellulose and lignin tend to dissolve under such conditions, which directly influences the durability of the fiber in cementitious matrices (Jamshaid et al., 2023).

Bamboo deserves special mention for its potential as reinforcement in ultra-high-performance concrete (UHPC). Recent studies have shown that bamboo fibers have a cellulose content of 54.49% and a modulus of elasticity compatible with structural applications. Experimental results indicated that incorporating 18-mm-long bamboo fibers at 1.0% by volume produced a 21.9% increase in the compressive strength of UHPC, whereas raising the volume fraction to 1.5%, for fibers of the same length, produced a 40.5% increase in flexural strength (Li et al., 2024).

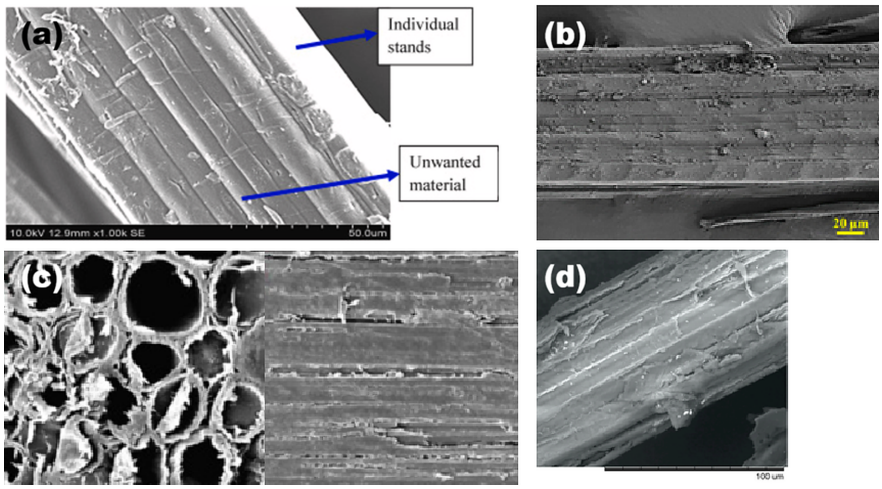


Figure 2 – Micrographs obtained by scanning electron microscopy (SEM) of the plant fibers most widely used in cementitious composites: (a) sisal, (b) jute, (c) bamboo and (d) sugarcane bagasse, highlighting the fibrillar structure.

Source: a) Muthukumar et al., 2025; b) Chowdhury et al., 2025; c) Lv et al., 2025; d) Sakura et al., 2025.

Sugarcane represents a resource of considerable relevance in the Brazilian context, given the high volume of bagasse generated by the sugar and ethanol sector. Processed and dried sugarcane bagasse may be used both as a reinforcing fiber and, in the form of sugarcane bagasse ash (SCBA), as a pozzolanic material for partial cement replacement (Jamshaid et al., 2022). Experimental results indicate that the addition of 0.75% by volume of 40-mm-long sugarcane bagasse fibers raised the compressive strength by 33.14% and the flexural strength by 150.09% relative to the reference concrete (Kurpinska et al., 2022; Sales et al., 2024).

The use of these plant wastes in engineering matrices not only improves the thermal and acoustic properties of the resulting materials but also mitigates the environmental

impact arising from anaerobic decomposition in landfills or open-air burning, common practices in the disposal of residual biomass (Pimentel; Beraldo; Savastano Júnior, 2006).

1.3. Agro-industrial by-products as functional aggregates

In addition to long reinforcing fibers, agro-industrial byproducts may be processed to act as functional lightweight aggregates in concretes. Rice husk ash (RHA), SCBA, coconut husk, and bone and eggshell fragments are examples of wastes with pozzolanic potential and/or with potential as partial substitutes for conventional fine aggregates (Islam et al., 2024).

The integration of these byproducts into construction responds to the need to mitigate the environmental impact of the cement industry, which is responsible for a significant share of global CO_2 emissions. Wastes rich in silicon and aluminum, such as cereal husks and straws, sugarcane bagasse, and various plant residues, have been repurposed as functional aggregates or supplementary cementitious materials.

When rice husk is burned under controlled conditions, the resulting RHA has a high amorphous SiO_2 content (85%–93%) and becomes a highly reactive material that contributes to the refinement of the microstructure of the cement paste and to the strengthening of the ITZ (Islam et al., 2024). The high amorphous silica content favors pozzolanic reactions with calcium hydroxide ($Ca(OH)_2$), resulting in the additional formation of calcium silicate hydrate (C-S-H), which reduces porosity and improves the durability of the composite. These microstructural modifications result in macroscopic gains, such as increased mechanical strength and greater resistance to the penetration of aggressive agents.

RHA is obtained by the combustion of the husk, which converts about 20% of its mass into an ash with a porous cellular structure and a high specific surface area. When produced under controlled conditions, RHA may reach amorphous silica contents between 85% and 93%, conferring high pozzolanic reactivity. This property allows the ash to react with the calcium hydroxide generated during the hydration of Portland cement, forming new cementing compounds that improve the mechanical strength and durability of the composites. In addition to the husk, rice straw also concentrates silica in its leaves and stalks, representing a further resource with pozzolanic potential.

Beyond their pozzolanic function, these byproducts act as functional aggregates that refine the microstructure of the cementitious matrix, reducing permeability and increasing resistance to attack by aggressive agents such as chlorides and sulfates. Thus, the use of RHA in structural concretes not only optimizes technical performance but also offers

economic advantages by reducing clinker consumption and by making use of locally available wastes.

Recent studies with local clay and RHA in the production of artificial lightweight aggregates for structural concrete have shown that a suitable combination of materials makes it possible to obtain strength classes compatible with structural applications, with improvements in the modulus of elasticity and in the resistance to chloride penetration (Islam et al., 2024).

However, the compositional variability of these wastes, associated with differences in the origin of the biomass and/or in the processing conditions, as well as the strong dependence of the properties on burning temperature and time, may result in inconsistent behavior of the materials, requiring rigorous quality control during their production and application (Thiedeitz et al., 2020). In general, the use of agro-industrial byproducts as functional aggregates represents a promising strategy for the development of more sustainable and durable cementitious composites, especially when integrated with optimized mix design approaches and hybrid material systems.

The use of agro-industrial byproducts as functional aggregates is therefore driven by the need to decarbonize the construction sector. The incorporation of these wastes reduces the embodied energy of building elements and mitigates environmental liabilities, such as the air pollution resulting from the indiscriminate burning of biomass, promoting a circular economy in the sector (Pimentel; Beraldo; Savastano Júnior, 2006).

2. MECHANISMS OF STRUCTURAL REINFORCEMENT IN CEMENTITIOUS COMPOSITES

2.1. Interfacial transition zone (ITZ)

The mechanical performance of a cementitious composite is governed to a large extent by the quality of the interface between the dispersed phase (aggregate or fiber) and the hydrated cement matrix. The ITZ is a microstructural region with a typical thickness of 10 to 50 μm around the aggregate particles. It originates primarily from the "wall effect," which prevents the efficient packing of the cement particles next to the aggregate surface, resulting in a region with a higher local water/cement ratio. Microstructurally, the ITZ is characterized by a high porosity, resulting from the inefficient initial packing of the cement particles and the consequent accumulation of free water at the interface. This environment favors the formation of a high concentration of portlandite ($Ca(OH)_2$) crystals that tend to grow with a preferential orientation, establishing brittle cleavage planes that weaken the region. In addition, a deficit of C-S-H is observed in comparison

with the bulk cement paste, which results in a less dense local matrix with a reduced capacity to transfer mechanical stresses between the phases of the composite (Scrivener; Nemati, 1996; Bentur; Mindess, 2006; Mehta; Monteiro, 2014).

In the case of recycled aggregates, the complexity increases owing to the presence of the residual mortar adhered to the original natural aggregate. This gives rise to a double ITZ: an internal interface (between the old aggregate and the residual mortar) and an external interface (between the residual mortar and the new paste). This configuration intensifies microstructural heterogeneity and promotes the nucleation of microcracks under loading (Poon; Shui; Lam, 2004; Dafedar et al., 2024). Research using scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis has shown that controlled pre-wetting and accelerated carbonation treatments of RCAs can densify the ITZ, reducing interfacial porosity and increasing the compressive strength of the resulting composites (Kępniak; Chylinski; Woyciechowski, 2025; Zhang et al., 2025).

For plant fibers, the ITZ presents additional challenges arising from the hydrophilic nature of cellulose. The fiber absorbs water during mixing and swells; subsequently, on losing this water to hydration or evaporation, the fiber shrinks, leaving a peripheral void that weakens the matrix–fiber bond. Moreover, the stability of the interface is compromised by the highly alkaline environment (pH > 12), which may degrade the hemicellulosic and lignin components (Jamshaid et al., 2023).

A critical phenomenon at this interface is the mineralization mechanism, in which the cement hydration products (such as portlandite) precipitate in the lumens and cell walls of the fiber over time. Although this process may initially increase the stiffness of the system, it frequently leads to the embrittlement of the composite, reducing its energy absorption capacity and its long-term ductility (Toledo Filho et al., 2000; Savastano; Warden; Coutts, 2005; Neto et al., 2025).

2.2. Toughening mechanisms and impact resistance

The impact resistance of fiber-reinforced cementitious composites is governed by energy absorption mechanisms distinct from those that determine static compressive strength. As presented in Figure 3, the main mechanisms identified in the literature are: fiber pull-out (frictional extraction), crack deflection, multiple cracking, and fiber bridging (restraint of open cracks by fibers that cross the crack surfaces) (Li et al., 2024; Tao et al., 2024; Neto et al., 2025).

The efficiency of these toughening mechanisms depends on the nature of the fiber–matrix interface. In composites reinforced with natural fibers, the surface roughness and the water absorption capacity of the fiber influence the ITZ. Whereas excessive

adhesion may lead to brittle rupture of the fiber, optimized adhesion favors controlled slip (pullout), which is the main mechanism of kinetic energy dissipation (Monteiro; D'Almeida, 2006; Sharan Chandran; Padmanabhan, 2019; Qiao et al., 2026).

The fracture energy (G_f), which corresponds to the area under the load–deflection curve beyond the peak load in the three-point bending test, is the most direct indicator of the toughness of the composite. The incorporation of natural fibers in optimum proportions (typically between 1.0% and 2.0% by volume) may raise the fracture energy by up to 300% relative to the unreinforced matrix, converting the brittle behavior typical of concrete into a semi-plastic behavior with appreciable deflection (Mat Jusoh et al., 2021; Chen et al., 2023; Neto et al., 2025; Olanrewaju; Oladele; Adelani, 2025).

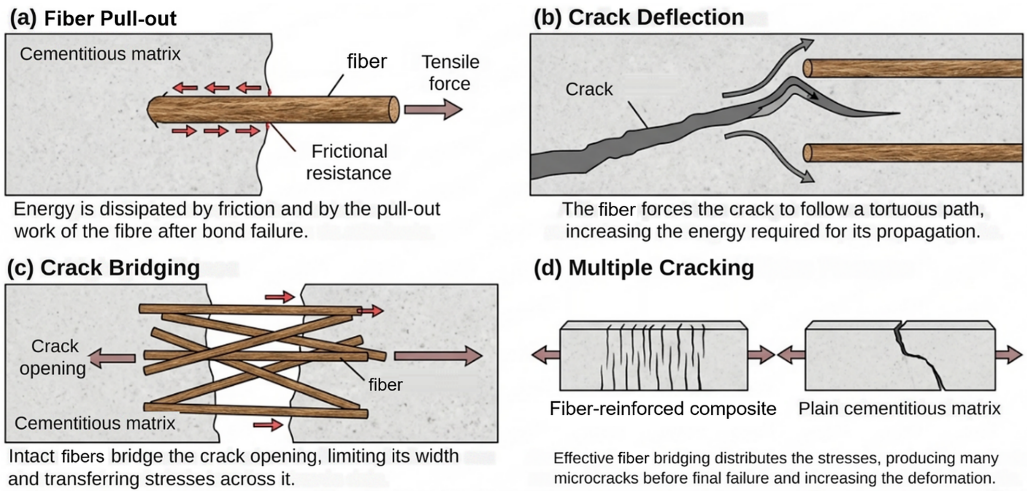


Figure 3 – Schematic representation of the toughening mechanisms in cementitious composites reinforced with natural fibers: (a) fiber pullout, (b) crack deflection, (c) crack bridging, and (d) multiple crack formation.

Impact resistance may be quantified by the drop-weight test in accordance with ACI 544.2R (ACI, 1989), by the adapted Charpy test, or by the projectile impact test. In composites reinforced with natural fibers, the impact energy absorption increases in proportion to the fiber content, up to the saturation point of the matrix, beyond which the non-homogeneous distribution of the fibers introduces zones of stress concentration (Li et al., 2024).

Beyond load capacity, the addition of plant fibers decisively alters the failure modes, reducing scabbing (detachment of fragments from the rear face) and spalling (chipping of the impact face), thereby preserving structural integrity even after fragmentation of the matrix (Silva; Mobasher; Toledo Filho, 2009).

2.3. The shear-lag model for fiber reinforcement

The shear-lag model (load transfer by shear) is the most established theoretical framework for analyzing the efficiency of reinforcement by short fibers dispersed in a continuous matrix. In this model, the tensile stress in the fiber (σ_f) as a function of the distance z from its end is described by Equation 1:

$$\sigma_f(z) = E_f \epsilon_c \left[1 - \frac{\cosh(\beta z)}{\cosh(\beta l)}\right] \quad (1)$$

where E_f represents the modulus of elasticity of the fiber (GPa); ϵ_c is the average strain of the matrix in the longitudinal plane of the fiber; l is half the length of the fiber (mm); and β is the shear-lag parameter.

The critical transfer length (L_c), below which the fiber debonds from the matrix before reaching its rupture stress, is given by Equation 2:

$$L_c = \frac{\sigma_f \cdot d}{2\tau} \quad (2)$$

where σ_f represents the tensile strength of the fiber (MPa); d is the diameter of the fiber (mm); and τ is the fiber–matrix interfacial bond stress (MPa).

For fibers with $L_f > L_c$, the strength of the composite is governed by rupture of the fiber; for $L_f < L_c$, by pullout. The optimum value of fiber length for maximizing energy absorption lies in the range $L_f \approx 2L_c$ to $3L_c$ (Li et al., 2024; Neto et al., 2025).

3. MECHANICAL PERFORMANCE: COMPRESSIVE AND IMPACT STRENGTH

3.1. Concretes with recycled concrete aggregates (RCA)

The replacement of natural aggregates by RCAs generally entails a reduction in compressive strength, the magnitude of which depends critically on the replacement ratio, on the quality of the parent concrete, and on the treatment given to the aggregates. Recent Brazilian studies have confirmed that concretes with total replacement of natural aggregates by RCAs reached mean 28-day compressive strengths above 18 MPa, compatible with nonstructural applications according to ABNT NBR 6118:2023 (ABNT, 2023; Machado; Angulo, 2025).

Research conducted with different replacement ratios (0%, 12.5%, 25%, 50%, and 100%) shows the high variability of the results, with a standard deviation of 5.6 MPa and a coefficient of variation of 24.9% for the 100% replacement series; only 36% of the

specimens reached the minimum characteristic strength for structural concrete ($f_{ck} \geq 20$ MPa) (Miranda et al., 2025). Table 2 summarizes these results.

Table 2 – Compressive strength (MPa) of concretes with different RCA proportions relative to the reference concrete

RCA proportion (%)	Binder	f_c mean (MPa)	Relative variation (%)	COV (%)	RCA treatment
0 (reference)	Portland CP II-F	32.1	–	6.2	–
12.5	Portland CP II-F	30.8	-4.0	8.1	None
25	Portland CP II-F	29.3	-8.7	10.4	None
50	Portland CP II-F	26.5	-17.4	18.6	None
100	Portland CP II-F	22.4	-30.2	24.9	None
50	CP V-ARI + silica fume	30.2	-5.9	9.8	Pre-soaking
100	CP V-ARI + silica fume	27.6	-14.0	12.1	Pre-soaking
100	Portland + fly ash	25.8	-19.6	14.3	Accelerated carbonation
100	Polyester resin (polymer concrete)*	96.0	+7.8	5.1	None

Source: Ullah et al., 2024; Kępniak; Chylinski; Woyciechowski, 2025; Miranda et al., 2025; Zhang et al., 2025.
*Note: the reference value for comparison is 89.1 MPa, obtained for polymer concrete produced with natural aggregates.

Polymer concrete with RCAs has shown distinct and promising behavior: the total replacement of natural aggregates by RCAs resulted in a compressive strength of 96 MPa, higher than the 89.1 MPa obtained with natural aggregates, a phenomenon attributed to the formation of a double layer of resin and limestone on the surface of the recycled grains, which densifies the polymer–aggregate interface (Ullah et al., 2024). This result shows that the binder substantially affects the response of RCAs to compressive loading.

Studies with pre-soaking treatments of RCAs revealed that the controlled absorption of water by the residual mortar during mixing may produce internal curing, which promotes additional hydration of the cement in the ITZ, improving the density and the strength of this region. The layer of fines adhered to the surface of the RCAs, when suitably controlled, may seal surface pores and reduce interfacial porosity, as revealed by analysis of the C-S-H phase under electron microscopy (Kępniak; Chylinski; Woyciechowski, 2025).

The replacement of up to 30% of the natural aggregates by RCAs is indicated as a reasonable technical threshold for concrete pavements, maintaining compressive strength above 20 MPa and a California Bearing Ratio (CBR) above 60%, with cost reductions on the order of 25% (Gomes, 2025; Pastor et al., 2025). For more demanding structural applications, the combined use of mineral additions (silica fume, fly ash, limestone) and dispersing admixtures is recommended, since these compensate for the negative effects of the residual mortar on the ITZ (Gomes, 2025).

3.2. Cementitious composites reinforced with plant fibers

The mechanical behavior of cementitious composites reinforced with plant fibers follows a nonmonotonic relationship between fiber content and compressive strength. The literature consistently reports a phase of strength gain for fiber contents between 0.5% and 2.0% by mass, followed by a pronounced drop at higher contents, associated with the introduction of pores and fiber agglomerates that compromise the compactness of the matrix (Jamshaid et al., 2022; Neto et al., 2025).

Among the most extensively studied cellulosic fibers, jute showed the best results in terms of increases in compressive strength (+20.2% at 0.4% by mass) and tensile strength (+137.7% in the splitting tensile test), whereas sisal showed increases of 11.9% in compressive strength and 103.8% in tensile strength under optimum conditions of content and length (Olanrewaju; Oladele; Adelani, 2025). For sugarcane fiber (bagasse), experimental results with 0.75% by volume of 40-mm-long fibers indicated increases of 33.14% in compressive strength and 150.09% in flexural strength (Sales et al., 2024).

In studies with UHPC reinforced with bamboo fibers, greater fiber lengths were found to enhance the gains in compressive and flexural strength, at the expense of workability. As presented in Section 1.2, the gains reach 21.9% in compression and 40.5% in flexure (Li et al., 2024). These results give bamboo fibers a mechanical performance profile superior to that of other natural fibers in high-performance matrices.

For hybrid composites combining different plant fibers, the synergistic effect (hybrid effect) yields a performance superior to the simple sum of the contributions expected from each fiber in isolation. The mixture of 75% banana pseudostem fibers with 25% sugarcane bagasse fibers resulted in increases of 13.92% in compressive strength and 64.43% in flexural strength, exceeding the values obtained with each fiber alone (Sales et al., 2024).

3.3. Impact resistance

Impact resistance represents a critical design parameter in structures subjected to dynamic loading and high strain rates, such as industrial pavements, retaining elements, tunnel linings, and buildings in seismic zones. In such scenarios, the conventional cementitious matrix (intrinsically brittle) fails catastrophically owing to the rapid propagation of cracks. In contrast, cementitious composites reinforced with natural fibers exhibit performance superior to that of conventional concrete in the drop-weight test, with increases in absorbed energy of 150%–400%, depending on the fiber type and content (Neto et al., 2025).

The dominant mechanism of impact energy absorption in natural-fiber composites is ductile pullout, resulting from the deformability of the fiber and from its moderate bond to the cementitious matrix. This phenomenon occurs in the ITZ, where the surface roughness of the fibers allows the filament to slide in a controlled manner through the matrix after cracking, dissipating kinetic energy through friction. For this mechanism to be efficient, the length of the fiber (L_f) must be greater than its critical length (L_c), ensuring sufficient anchorage for energy dissipation along the entire embedded length (Li et al., 2024).

However, the efficiency of this mechanism is sensitive to the stiffness of the fiber. Whereas coconut and bamboo fibers, owing to their greater deformability, favor slip, fibers such as jute and sisal have a higher modulus of elasticity and a lower strain at rupture. This high stiffness may lead to premature failure of the fiber before it is fully pulled out, reducing the residual load capacity of the composite. Optimization of impact resistance therefore requires a balance between the tensile strength of the fiber and the bond energy at the fiber–matrix interface, preventing excessive adhesion from rendering the material brittle.

4. TREATMENT AND OPTIMIZATION STRATEGIES FOR NATURAL WASTE AGGREGATES

4.1. Physicochemical and biological treatments

The most widespread physical treatment for RCAs is pre-soaking, a technique in which the aggregates are saturated for 24 hours before mixing, reducing water absorption during the hydration process and stabilizing the effective w/c ratio of the concrete (Kępniak; Chylinski; Woyciechowski, 2025). Variations of the method include pre-soaking with a dilute cementitious solution, which promotes the precipitation of C-S-H on the porous surface of the RCA, densifying the ITZ even before final mixing.

In accelerated carbonation, exposing RCAs to atmospheres with a high CO_2 concentration (1%–5%) converts $Ca(OH)_2$ and C-S-H into $CaCO_3$, which crystallizes in the pores of the residual mortar, reducing water absorption by up to 18.1% and the crushing index by a similar magnitude, according to results reported for the combined carbonation and microbially induced calcite precipitation (MICP) treatment (Zhang et al., 2025).

The main limitation of plant fibers in cementitious matrices is the progressive alkaline degradation of cellulose and hemicellulose in environments with a pH above 12. The treatment strategies most widely employed to mitigate this phenomenon are:

(a) Alkali treatment (mercerization): immersion of the fibers in NaOH solution (2-10% by mass, 30–60 min at room temperature), which dissolves hemicelluloses, part of the lignin, and surface waxes, increasing the roughness and the available surface area and improving adhesion to the matrix (Chen et al., 2023; Jamshaid et al., 2023);

(b) Silylation: treatment of the fibers with organosilane compounds that create covalent bridges between the cellulose surface and the silica of the cement, substantially improving interfacial adhesion and resistance to alkaline hydrolysis (Jamshaid et al., 2023);

(c) Cement pre-impregnation: the fibers are immersed in dilute cement paste before mixing, which creates a densified pre-interface and reduces the water absorption of the fiber during hydration;

(d) Biological treatments (MICP): microbially induced $CaCO_3$ precipitation on the surface of the fibers and of the RCAs creates a protective mineral layer, combining the benefits of reduced porosity and increased adhesion, with promising results in recent studies of hybrid aggregates (Kępniak; Chylinski; Woyciechowski, 2025).

The choice of treatment strategy depends on the balance between the desired mechanical performance and the economic feasibility of the project. Whereas methods such as pre-soaking and mercerization tend to offer lower-cost, easily implemented solutions, advanced techniques such as accelerated carbonation and MICP offer the greatest durability gains, mitigating the intrinsic deficiencies of natural and recycled materials. The optimization of these interfaces is therefore the determining factor for the technical feasibility of more sustainable and resilient cementitious composites.

4.2. Formulation and mix design of the composites

The mix design of composites with natural waste demands a more extensive prior characterization protocol than that used for conventional aggregates. Before formulation, it is essential to determine physical and chemical parameters such as true and apparent specific gravity, water absorption, shape index, particle size distribution, crushing

resistance (Los Angeles for RCAs), chemical composition by X-ray fluorescence (XRF), and mineralogical composition by XRD (ABNT, 2021a).

The Andreasen and Andersen curve, which describes the optimum particle size distribution for maximizing packing, is a valuable tool for the mix design of composites with RCAs, especially in mixtures with fillers and mineral additions (Gomes, 2025). This model makes it possible to reduce intergranular voids, decreasing the amount of cement paste required for filling.

Furthermore, the use of new-generation dispersing admixtures such as polycarboxylate ethers is essential to compensate for the increased water demand of the RCAs. These superplasticizers make it possible to maintain the effective w/c ratio and the desired workability without the need to add water, thus preserving the mechanical strength and durability of the final composite.

4.3. Real-world applications

In 2023 and 2024, the company Jetra Construtora carried out an industrial pavement project in São Paulo using concrete with 30% replacement of coarse aggregates by RCAs originating from controlled demolitions on the same site, with the addition of limestone and a dispersing admixture. Quality control results indicated a mean compressive strength of 28 MPa (specified f_{ck} = 25 MPa), with a cost reduction of 22% relative to the conventional mix and a 6% decrease in CO_2 emissions associated with the extraction of virgin aggregates (Gomes, 2025).

Rural housing programs in Vietnam and Thailand have employed structural panels based on concrete reinforced with treated bamboo fibers as a partial replacement for steel reinforcement in slabs and low-rise load-bearing walls. In situ performance evaluations documented compressive strengths between 22 and 30 MPa with bamboo fiber (18 mm) contents of 1.0% to 1.5%, compatible with the requirements of ground-floor slabs and load-bearing walls of one- to two-story buildings (Li et al., 2024).

Applied research developed in partnership with textile industries in the Northeast of Brazil assessed the feasibility of industrial floors manufactured with a composite of cement, sand, and residual sisal fibers from textile processing, at a content of 1.5% by volume. The specimens exhibited a drop-weight impact resistance 2.8 times that of conventional concrete in the ACI 544.2R test, with a compressive strength of 29 MPa (C25), demonstrating that sisal textile waste may be reused directly, without additional processing, in industrial flooring applications (Olanrewaju; Oladele; Adelani, 2025).

In a pilot-scale study carried out in Bangladesh, artificial lightweight aggregates were produced from local clays and RHA in optimized proportions and were incorporated into

structural concrete with partial replacement (30–50%) of natural crushed stone. The resulting concretes reached a compressive strength of 25 MPa and showed a 12% improvement in the dynamic modulus of elasticity relative to concrete with pure clay, in addition to an 18% reduction in thermal conductivity, indicating potential for roof slabs in tropical zones (Islam et al., 2024).

Research conducted in South Korea developed a sustainable UHPC incorporating recycled concrete powder (RCP) as a partial substitute for cement (5%–15%) and steel fibers from waste tires (WTSF) as reinforcement. The system reached a maximum compressive strength of 129 MPa with 5% RCP replacement, and a life cycle assessment (LCA) demonstrated significant reductions in global warming potential (GWP) and fossil resource depletion potential relative to conventional UHPC (Mehmood et al., 2025).

In view of this expanding scenario, the development and quality control of composites with natural solid waste must be guided by a set of national and international standards. In Brazil, the main standards are:

- ABNT NBR 15116:2021 – Recycled aggregates for use in Portland cement mortars and concretes: requirements and test methods (ABNT, 2021a);
- ABNT NBR 6118:2023 – Design of concrete structures: procedure (ABNT, 2023);
- ABNT NBR 5739:2018 – Concrete: compression test of cylindrical specimens (ABNT, 2018);
- ABNT NBR 12655:2022 – Portland cement concrete: preparation, control, receipt and acceptance (ABNT, 2022);
- ABNT NBR 7211:2019 – Aggregates for concrete: specification (ABNT, 2019a);
- CONAMA Resolution No. 307/2002 (and updates) – Guidelines for CDW management (Brasil, 2002).

At the international level, the main references are ASTM C1609/C1609M – Flexural performance of fiber-reinforced composites: beam method (ASTM, 2024); ACI 544.2R – Measurement of the impact property in fiber-reinforced concrete (ACI, 1989); and EN 206:2021 – Concrete: specification, performance, production and conformity (Europe) (CEN, 2021).

5. FUTURE PERSPECTIVES AND CHALLENGES

The field of natural solid waste aggregates for structural reinforcement presents a set of challenges and opportunities that outline the research agenda for the coming years. Among the main scientific and technological challenges identified, the following stand out:

Long-term durability: the progressive alkaline degradation of plant fibers in cementitious matrices remains the central obstacle to structural applications with a long service life. The development of more durable surface treatments—based on nanosilica, graphene oxide, or biodegradable polymer coatings—represents a promising avenue for innovation (Jamshaid et al., 2023; Tao et al., 2025).

Variability and quality control: the intrinsic heterogeneity of CDW and the natural variability of plant fibers introduce high coefficients of variation in the mechanical properties of the composites, requiring the development of testing protocols and acceptance criteria specific to these materials, which are still absent from Brazilian standards (Miranda et al., 2025).

Integration with 3D printing: additive manufacturing (3D concrete printing) offers unprecedented opportunities for the use of concretes with RCAs and plant fibers, since printing systems allow precise control of the geometry and orientation of the fibers within the composite. Recent research has shown that CDW aggregates, forestry residues, and agricultural waste can be incorporated into printable mixtures, favoring full-cycle low-carbon construction systems (Tao et al., 2025).

Computational modeling and machine learning: the enormous diversity of variables involved in the formulation of composites with natural waste—fiber type and content, RCA replacement ratio, type of mineral addition, w/c ratio, and curing conditions—renders traditional empirical models insufficient to cover the design space. The integration of machine learning techniques (artificial neural networks, evolutionary algorithms) with representative experimental databases constitutes an innovative approach to the multi-objective optimization of these systems (Olanrewaju; Oladele; Adelani, 2025).

Systemic sustainability and circular economy: the assessment of the environmental impact of composites with natural waste must go beyond the analysis of the mix itself, incorporating LCAs that account for the energy costs of transport, processing, and treatment, as well as the environmental credits for avoided mineral extraction and for carbon sequestration in plant fibers (Mehmood et al., 2025).

The consolidation of natural waste as high-performance materials depends on overcoming these technical challenges. The combination of nanotechnology and computational optimization methods is the most promising path to aligning the construction industry with the principles of the circular economy and low-carbon construction.

6. FINAL CONSIDERATIONS

This chapter has shown that natural solid waste aggregates—both those of mineral origin (RCAs) and those of plant origin (fibers and particles)—constitute technically vi-

able components for the formation of cementitious composites with controlled mechanical performance. The compressive strength of composites with RCAs may be maintained above structural thresholds with replacement ratios of up to 30% for untreated RCAs, and potentially higher with accelerated carbonation, MICP, or pre-wetting treatments. Plant fibers, in turn, contribute significantly to impact and flexural strength, converting the brittle behavior of the cementitious matrix into a semi-plastic regime of high energy absorption.

The application examples presented confirm that the transfer of this knowledge from the laboratory to the construction site is technically feasible and economically competitive, especially when the costs of waste disposal and the environmental externalities avoided are taken into account. Despite the significant advances in the use of natural solid waste in cementitious composites, challenges related to durability, variability, and standardization still limit its large-scale application. The development of more efficient physicochemical techniques and treatments, together with the improvement of technical standards, is expected to establish these materials as sustainable alternatives to conventional aggregates.

In this context, the consolidation of standards, the development of standardized treatment protocols, and the incorporation of advanced computational tools for mix design optimization, together with a better understanding of long-term degradation mechanisms and the optimization of the matrix–reinforcement interface, are the main drivers for the expansion of these technologies in Brazilian and international construction practice.

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PART III

People, equity, and education

CHAPTER 9

Women in the construction industry: structural inequalities, institutional challenges, and interfaces with SDG 5

Michele de Jesus Nogueira, Mostafa Galal Abdelfattah Mohamed Aboelkheir, Ana Paula Branco do Nascimento, Guilherme Leite Gaudereto, Rodrigo Teixeira Bento

1. INTRODUCTION

The presence of women in the construction industry continues to be marked by a persistent paradox. On the one hand, women's educational attainment has increased and access to engineering programs has expanded, indicating important advances in women's education and professional qualification for work in the sector (Ferreira, 2023; Achon et al., 2024). Experiences of leadership, entrepreneurship, and participation in different areas of work can also be observed, although unevenly and often conditioned by institutional and cultural barriers (Rocha; Gitahy, 2022; Macedo et al., 2024). On the other hand, the construction industry continues to operate on strongly masculinized historical foundations, with low female representation in operational and decision-making positions, persistent wage inequalities, retention difficulties, and working conditions still poorly adapted to gender diversity (Ferreira, 2023; Ghanbaripour et al., 2023; Achon et al., 2024).

This tension cannot be understood solely as a problem of quantitative access. Women's participation in the construction industry is permeated by power relations, by a sexual division of labor that values masculinized attributes and devalues competencies associated with women, and by institutional arrangements that often treat inclusion as a peripheral or reputational agenda. Consequently, the problem is not limited to increasing the number of women in the sector, but requires examining the organization of work, progression criteria, safety regimes, construction-site culture, leadership patterns,

and the regulatory and political mechanisms that sustain, tolerate, or confront these asymmetries (Stamarski; Son Hing, 2015; Santos, 2023; Macedo et al., 2024; Medina Filho et al., 2024).

Within the 2030 Agenda, this debate is directly linked to Sustainable Development Goal 5 (SDG 5), particularly the targets related to eliminating discrimination and violence, expanding women's participation and leadership, and strengthening gender-sensitive policies and institutional frameworks. However, gender equality, when considered from the perspective of the construction industry, is not limited to SDG 5. It is connected to decent work, innovation, education, reduced inequalities, occupational health, and institutional quality, reinforcing the need to treat gender as a cross-cutting dimension of sectoral sustainability rather than as an ancillary issue (Amaral; Peixoto, 2021; Candido; Canguçu, 2021; Andrade, 2022; Leal Filho et al., 2023).

Based on this understanding, the chapter assumes that gender inequality in the construction industry is manifested not only as a deficit in female participation, but as an expression of an institutional, occupational, and symbolic configuration that conditions women's access, retention, progression, and recognition in the sector.

The discussion is organized around six interconnected axes. The first examines female representation and the configuration of the sector. The second discusses structural, cultural, and symbolic barriers. The third addresses violence, safety, and conditions for retention in the workplace. The fourth focuses on education, qualification, professional transition, and leadership. The fifth analyzes institutional policies, governance, and interfaces with SDG 5. The sixth addresses intersectionalities and contextual variations that intensify or reconfigure gender inequalities in the construction industry.

This chapter results from an analytical narrative review of national and international studies on women in the construction industry, gender inequalities, institutional governance, and interfaces with SDG 5. The source corpus comprised 52 technical and scientific documents identified in the Scopus and Semantic Scholar databases using the descriptors Civil Construction, SDG 5, Sustainability, Gender Equality, and Women in Civil Construction, in both Portuguese and English. No prior time frame was set; the documents gathered span publications from 2010 to 2024. The analysis presented in this chapter draws on studies directly situated in the construction sector and, when analytically relevant, studies from related fields, such as public policy, gender-based violence, organizational diversity, and professional education. These related studies are used through explicit analogy to broaden the understanding of the institutional dynamics that condition women's entry, retention, and progression in historically masculinized occupational contexts.

Within this scope, the central argument developed throughout the chapter is that gender inequality in the sector cannot be reduced to women's low numerical presence, but is structured through persistent institutional barriers, informal recognition criteria, opacity in progression processes, material inadequacies in the work environment, and intersectional asymmetries that remain insufficiently addressed by the technical literature and organizational practices.

2. FEMALE REPRESENTATION AND THE CONFIGURATION OF THE SECTOR

2.1. Between educational progress and low occupational participation

Female representation in the construction industry remains low, even though women's educational trajectories show substantial progress in several contexts. The Brazilian case clearly illustrates this dissociation. Achon et al. (2024) show that women's participation among entrants to the Civil Engineering program at UFSCar rose from 3.33% in 1978 to 33.72% in 2022, whereas women accounted for approximately 30% of engineering students nationwide in 2019. Even so, in 2022, slightly more than 22% of professionals registered as civil engineers with the Federal Council of Engineering and Agronomy (CONFEA) were women, and in 2021 only 10.85% of formal employment relationships in the construction industry were held by women. Ferreira (2023) reinforces this mismatch by indicating that, considering the sector as a whole, including formal and informal work, women accounted for 3.61% of workers in 2021. Considering formal employment relationships alone, female participation rose from 7.52% in 2006 to 10.84% in 2021.

This pattern is not isolated. Ghanbaripour et al. (2023) observe that, in different international contexts, female participation in construction usually ranges between 9% and 13%. For Australia, the authors report that female participation declined from 17% in 2006 to 12.9% in 2020. In Malaysia, Al Salaheen et al. (2024) report a recurring presence of institutions with fewer than five women on their staff, indicating a low critical mass of women even in companies already experimenting with Industry 4.0 technologies. In apprenticeship programs in Nigeria, Adah, Daniel, and Tunji-Olayeni (2024) likewise describe low participation and the marked underrepresentation of women. This is therefore not a localized problem, but an international pattern of restricted entry, fragile retention, and unequal advancement in a sector whose historical identity remains anchored in the masculinization of productive work.

The persistence of this low representation must be interpreted on two simultaneous scales. At the first, it is an effect of occupational segmentation within the sector, which concentrates women in specific niches, such as administrative roles, technical support,

finishing, cleaning, or materials quality control, while restricting their presence in activities perceived as central to the identity of the construction site, such as masonry, concrete work, assembly, heavy-equipment operation, and direct site supervision (Silva; Osterne, 2014; Rocha; Gitahy, 2022; Ferreira, 2023). At the second, it is a broader institutional effect, in which education, the labor market, professional culture, and management regimes reproduce successive filters that prevent expanded educational access from automatically translating into occupational and hierarchical equality (Stamarski; Son Hing, 2015; Zapata; Truyol, 2022).

The problem, therefore, concerns not only numerical presence but also relative position within the sector. Even when women enter, they are less likely to occupy highly valued positions, remain more exposed to precarious employment relationships, and face greater difficulty advancing into positions of authority. Macedo et al. (2024) show that, in 2017, only 39.1% of management positions in their study context were held by women, despite women having a higher proportion of master's degrees. Santos and Prado (2024), in assessing national SDG 5 indicators, report that women held 34.9% of managerial positions, a figure that still indicates underrepresentation. The study by Silva and Lima (2022), focused on the Judiciary, illustrates that even in institutions with relatively greater feminization, advancement to top positions does not keep pace with women's presence in the occupational base. The analogy is useful for the construction industry because it reinforces a recurring mechanism: presence does not mean power.

Table 1 summarizes some of the main quantitative indicators reported in the studies. Its purpose is to show that the equality deficit in the construction industry does not result from an absolute absence of female participation, but from an arrangement in which expanded access coexists with structural limits on entry, progression, and recognition.

Gender inequality in the construction industry is expressed not only in low aggregate female participation, but also in how that participation is distributed across functions, hierarchical levels, and decision-making spaces. The expansion of women's presence in higher education and in certain technical segments has not been matched, to the same extent, by their entry into positions offering greater stability, authority, and professional recognition. Accordingly, the analysis of female representation in the sector must go beyond the numerical dimension and simultaneously consider conditions of access, the types of positions occupied, remuneration patterns, opportunities for progression, and effective participation in decision-making spaces.

Table 1 – Selected indicators of representation and gender inequality in contexts related to the construction industry

Study	Context	Indicator	Data summary
Achon et al. (2024)	Brazil	Education and labor market	30% of engineering students in 2019; 22% of civil engineers in 2022; 10.85% of formal construction employment relationships in 2021.
Ferreira (2023)	Brazil	Sectoral participation	3.61% of the sector's workers (formal + informal) were women in 2021; in formal employment relationships, female participation was 10.84% in 2021.
Ghanbaripour et al. (2023)	Australia	Female participation	Female participation of 17% in 2006, reduced to 12.9% in 2020.
Al Salaheen et al. (2024)	Malaysia	Low critical mass	Institutions with fewer than 5 women: 27.3%; from 5 to 10: 30.7%.
Silva and Osterne (2014)	Fortaleza	Female participation	5.9% of sector positions held by women in 2010; predominance in laborer roles.
Macedo et al. (2024)	Brazil	Management	39.1% of management positions held by women in 2017, despite women's higher educational attainment.
Wagner and Kulwiec (2022)	United States	Building trades	Women account for approximately 3% of construction trade occupations in the United States.

2.2. Occupational segmentation, hierarchy, and the value of work

On construction sites, low representation cannot be separated from the way work is hierarchically organized. In Fortaleza, Silva and Osterne (2014) show that women remained concentrated in laborer, cleaning, grouting, and finishing activities, with no women serving as construction forepersons. In fieldwork in Rio Grande do Sul, Romcy and Brites (2015) identify a similar tension between the recognition accorded to female engineers and architects, on the one hand, and the invisibility of female support workers, on the other. Ferreira (2023) and Rocha and Gitahy (2022) interpret this pattern as an expression of the sexual division of labor: tasks associated with precision, cleanliness, care, or finishing are classified as more suitable for women, whereas activities defined as heavy, dangerous, or technically central remain symbolically masculinized.

This segmentation occupies a strategic position in the reproduction of inequalities. When women's work is displaced into niches perceived as peripheral, it tends to receive less recognition, lower pay, and weaker connections to promotion pathways. In other words, hierarchical underrepresentation is not merely a statistical reflection of low over-

all participation; it is actively produced by an organization of work that defines which functions count as the productive core and which may be treated as marginal. For this reason, the literature criticizes triumphalist interpretations based solely on the increase in the number of women in engineering programs or training initiatives, without examining the actual quality of the employment opportunities made available to them (Salamah; Widaningsih, 2022; Ghanbaripour et al., 2023; Achon et al., 2024).

Another recurring issue is wage inequality. Achon et al. (2024) estimate a wage difference of approximately 48.8% between men and women with completed higher education in the construction industry in 2021. Candido and Canguçu (2021) highlight disparities of 16.1% in 2015 and 22.3% in 2019 in broader organizational analyses. Amaral and Peixoto (2021) and Santos and Prado (2024), although outside the strict scope of the construction sector, show that income inequality and the burden of unpaid work are decisive components for understanding women's difficulty in occupying higher-prestige positions. Wage inequality, therefore, should not be read as an isolated remuneration problem, but as a condensed marker of segmentation, discrimination, and the devaluation of women's work.

If the configuration of the sector is read only through aggregate indicators, there is a risk of naturalizing women's low presence as a spontaneous result of occupational "preferences." The studies analyzed suggest a different interpretation: the sector is configured by formal and informal rules that guide recruitment, task allocation, everyday interactions, progression, and recognition. It is this configuration that must be questioned if the aim is to align the construction industry with SDG 5 in substantive rather than merely rhetorical terms.

3. STRUCTURAL, CULTURAL, AND SYMBOLIC BARRIERS

3.1. Rigid working hours, informal rules, and masculinized culture

Barriers to women's entry and retention in the construction industry are not limited to visible obstacles such as hiring or pay. A set of implicit rules, normative expectations, and organizational routines defines who legitimately belongs in the sector and under what terms that presence may be sustained. Ghanbaripour et al. (2023) summarize this problem by identifying four central dimensions in women's experiences in the Australian construction industry: working hours and family, gendered culture and informal rules, career opportunities, and perceptions of women's capabilities. The strength of this formulation lies in showing that exclusion operates not only through explicit prohibitions,

but through an environment that makes everyday retention difficult and continuously signals that women are outsiders on the construction site.

Long and rigid working hours appear as one of the most recurrent factors. Rather than being a merely technical element of production organization, they function as a selective mechanism because they presuppose an ideal worker free from caregiving responsibilities and fully available to meet intense work rhythms, short deadlines, and extended schedules. Ghanbaripour et al. (2023) argue that rigid working hours appear to be the priority factor to address. Al Salaheen et al. (2024), from a different perspective, identify work-life balance as one of the most significant barriers for women in construction. In apprenticeship programs, Adah, Daniel, and Tunji-Olayeni (2024) associate retention with family support, transportation, and minimum material conditions. The convergence among these studies suggests that the problem of retention is not merely individual and that overcoming it depends on reorganizing the temporal structures and expectations of work.

The sector's masculinized culture reinforces these barriers. Hostile environments, disbelief in women's competence, exclusion from work-related conversations, harassment, jokes, and the constant need to prove capability are repeatedly described. Macedo et al. (2024) report statements in which women said they had been told that construction sites were "not a place for women" and that they had to study more and demonstrate greater competence than men in order to be recognized. Silva and Osterne (2014), Romcy and Brites (2015), and Ferreira (2023) document similar prejudice on Brazilian construction sites. Salamah and Widaningsih (2022) show that this environment directly affects adaptation, mental health, satisfaction, and retention. In all these cases, organizational culture does not appear as an abstract backdrop, but as an everyday mechanism of attrition and selection.

The notion of a cultural barrier, however, should not be used vaguely. This culture materializes in procedures: it appears in hiring interviews that treat motherhood as a risk, in supervisors who associate authority with masculinity, in informal referral networks from which women are excluded, in unclear promotion criteria, and in biased interpretations of flexibility and performance (Romcy; Brites, 2015; Stamarski; Son Hing, 2015; Wagner; Kulwiec, 2022). This materialization is important because it shifts the debate from a generic moral critique of sexism to a concrete organizational critique of the practices through which it operates.

Table 2 organizes these barriers into recurring analytical categories identified in the studies. The comparison shows that the obstacles are not dispersed, but form a system in which culture, work organization, professional recognition, and infrastructure mutually reinforce one another.

Table 2 – Recurring barriers to women's entry, retention, and progression in the construction industry

Dimension	Recurring manifestations	Representative studies	Implications
Temporal	Long working hours; rigidity; work-family conflict	Ghanbaripour et al. (2023); Al Salaheen et al. (2024)	Increases attrition and restricts retention.
Cultural	Sexism; informal rules; disbelief in capability	Macedo et al. (2024); Rocha and Gitahy (2022); Romcy and Brites (2015)	Produces isolation and a constant need to prove value.
Organizational	Opaque promotions; limited mentoring; biased HR	Stamarski and Son Hing (2015); Ghanbaripour et al. (2023)	Reduces progression and leadership.
Material	Inadequate PPE; lack of tools; poor logistics	Serra and Maia (2021); Adah, Daniel, and Tunji-Olayeni (2024)	Compromises safety and retention.
Relational	Harassment; humiliation; exclusion from networks	Ferrari, Cabral, and Salhani (2020); Salamah and Widaningsih (2022)	Affects well-being, adaptation, and retention.
Symbolic	Association of the construction site with masculinity	Ferreira (2023); Silva and Osterne (2014)	Segments functions and devalues women's work.

3.2. Perceptions of capability, segregation, and devaluation

A second core set of barriers concerns perceptions of women's capabilities. In several studies, women's competence is not taken for granted, but treated as something that must be continually proven. Macedo et al. (2024) show that the legitimacy of women in positions of authority is often conditioned on extraordinary performance. Ghanbaripour et al. (2023) identify negative perceptions of women's capabilities as one of the four structural factors contributing to attrition. Rocha and Gitahy (2022) describe a sector in which the partial feminization of engineering has not resulted in equivalent recognition on construction sites. In practical terms, this means that women enter the workplace already under suspicion.

This devaluation does not operate only symbolically. It contributes to segregating women into tasks perceived as extensions of domestic work, care, or finishing, while reserving for men positions associated with strength, authority, and technical centrality. This logic appears both in studies of female construction workers and in analyses of management and leadership. It constitutes a double barrier: it lowers the value attributed to

the work women perform and restricts their access to the experiences considered necessary for future promotion. Thus, professional experience itself begins to be distributed unequally from the outset (Silva; Osterne, 2014; Rocha; Gitahy, 2022; Ferreira, 2023).

The literature also suggests that policies focused solely on "attracting" women tend to fail when they do not confront this matrix of devaluation. Ghanbaripour et al. (2023) note that policies aimed at increasing numbers without transforming practices and culture are perceived as insufficient. Stamarski and Son Hing (2015) offer a useful formulation by demonstrating how organizational structures, HR processes, and decision-makers' sexism combine to reproduce inequalities in selection, promotion, evaluation, and remuneration. The contribution of this model is to show that cultural barriers and administrative barriers are not separate spheres, but operate in an interconnected manner.

In summary, the decisive barrier is not a lack of women's interest in the construction industry. Rather, it is the persistence of an institutional and symbolic architecture that accepts women's entry under asymmetric, conditional, and often precarious terms. For this reason, the gender-equality agenda in the sector cannot be reduced to expanding training opportunities or occasional recruitment. Without transforming the implicit norms that define value, authority, and belonging, inclusion tends to remain partial and reversible.

4. VIOLENCE, SAFETY, AND CONDITIONS FOR RETENTION IN THE WORKPLACE

4.1. Gender-based violence, harassment, and institutional silence

Gender-based violence is addressed on at least three distinct but complementary levels. The first concerns direct violence, whether sexual, physical, psychological, or moral. The second refers to organizational violence, expressed through humiliation, harassment, devaluation, and the normalization of hostile practices. The third involves structural violence, through which the absence of protection, institutional slowness, underreporting, and weak reporting mechanisms transform the workplace and social life into contexts in which remaining safely becomes increasingly difficult. This distinction prevents the issue from being reduced to extreme episodes when, in fact, everyday and diffuse violence forms part of the mechanism of women's exclusion (Ferrari; Cabral; Salhani, 2020; Borges; Cabral, 2022; Diotto; Costa, 2023).

In the field of sexual violence, Amarijo et al. (2014) present a particularly troubling finding by identifying occupational ties to the construction industry among 25.6% of the perpetrators analyzed in records from a specialized Brazilian police station for crimes against women (Delegacia da Mulher). Although the study does not address labor relations in the construction industry, the findings allow for a cautious contextual compari-

son between occupational masculinization, gender vulnerability, and the need for institutional prevention and protection mechanisms. This relationship, however, should be interpreted as indicative and contextual rather than as direct evidence of sectoral causality. Cunha, Almeida, and Machado (2022), in examining reported episodes of domestic violence during the pandemic, reinforce how economic dependence, structural racism, difficulty accessing protection networks, and underreporting increase women's exposure to violence. These elements are decisive for considering women's retention at work, since labor trajectories do not unfold in isolation from domestic and community life.

In academic and corporate environments, Ferrari, Cabral, and Salhani (2020) show that workplace bullying, sexual harassment, humiliation, and devaluation are not perceived in the same way by men and women. Men's lower perception of the seriousness of these forms of violence and the institutional normalization of hostile practices hinder prevention and response. This point is central to the construction industry, where strongly masculinized organizational cultures tend to normalize aggressive language, exposure to embarrassment, and relational exclusion as part of everyday production. Studies of Brazilian construction sites and female leadership reinforce this interpretation by describing environments in which women's professional respect is often conditioned on a constant demonstration of competence and resilience (Silva; Osterne, 2014; Romcy; Brites, 2015; Macedo et al., 2024).

Violence, therefore, cannot be treated solely as an issue belonging to the criminal sphere or to protections external to the sector. It is part of the problem of labor management itself. Hostile environments increase turnover, reduce satisfaction, restrict learning, undermine leadership trajectories, and reinforce the perception that the subjective cost of remaining in the construction industry is disproportionately high for women. In this regard, the literature indicates that reporting channels, institutional communication, continuing education, and leadership accountability are constitutive dimensions of the equity agenda rather than reputational accessories (Stamarski; Son Hing, 2015; Ferrari; Cabral; Salhani, 2020; Diotto; Costa, 2023).

4.2. Safety, ergonomics, and adaptation of the construction site

In addition to relational and institutional violence, the material conditions of work also function as a filter for retention. Al Salaheen et al. (2024) identify fear of heights, work-life balance, musculoskeletal disorders, and exposure to harmful gases as relevant barriers for women in construction. The merit of the study does not lie in naturalizing these barriers as female limitations, but in showing that technologies and production reorganization can reduce them, for example through building information modeling (BIM)

for collaborative work, unmanned aerial vehicles (UAVs) for inspections at height, augmented and virtual reality (AR/VR) for training, and advanced materials to reduce environmental exposure. The implicit argument is important: part of what appears as female "incapacity" is actually the result of environments designed without consideration for bodily diversity, differentiated trajectories, and inclusive ergonomics.

Serra and Maia (2021) deepen this point by discussing the anthropometric inadequacy of PPE intended for women working in the construction industry. According to the authors, the scarcity of appropriate sizes, the absence of adaptations for pregnant workers, and the discomfort generated by equipment designed for male bodies affect safety, productivity, and health. This is particularly strong evidence because it demonstrates that exclusion is embedded in the very design of protective artifacts. When equipment does not properly fit a female worker's body, it becomes evident that the presumed user of the construction site continues to be conceived according to a male standard.

Salamah and Widaningsih (2022) complement this discussion by analyzing workplace adaptation factors at three levels: individual, interpersonal, and organizational. The study indicates that harassment, long working hours, stress, pressure, wage inequality, and lack of managerial support create an environment of low adaptability. This makes it possible to reinterpret safety in broader terms. It is not only a matter of preventing physical accidents, but of creating conditions in which female workers can learn, move through the workplace, be protected, be recognized, and develop a sustainable career trajectory in the sector.

This broader understanding of safety is consistent with SDG 5 because it brings gender equality closer to decent work, health, and institutional well-being. Rather than treating women's safety on construction sites as a residual or "special" issue, the literature suggests that inclusive adaptation of the work environment can raise the overall standard of the sector. Risk-reduction technologies, appropriate PPE, ergonomic design, revised routines, and anti-harassment protocols tend to benefit not only women but also the overall quality of labor relations and production processes (Serra; Maia, 2021; Salamah; Widaningsih, 2022; Al Salaheen et al., 2024).

5. EDUCATION, QUALIFICATION, PROFESSIONAL TRANSITION, AND LEADERSHIP

5.1. Entry pathways: outreach, apprenticeship, pre-apprenticeship, and training

Entry pathways for women's participation in the construction industry are diverse. They include experiences linked to higher education in engineering, university outreach

programs, technical training linked to public policies, pre-apprenticeship programs aimed at construction trades, and solidarity-economy enterprises. This diversity is important because it challenges the idea that women's inclusion depends exclusively on the traditional formal path of engineering education. Rather, the routes of entry are multiple and often associated with contexts of social vulnerability, unemployment, low educational attainment, or the pursuit of economic autonomy (Landerdahl et al., 2011; Landerdahl et al., 2013; Wagner; Kulwiec, 2022; Jorge; Borges; Bortolaso, 2024).

In the field of university education, Zapata and Truyol (2022) argue that institutional commitment to gender equality in engineering schools depends on three main factors: incorporating a gender perspective into the curriculum, faculty training, and the existence of clear protocols against discrimination. The study is decisive because it shifts the problem from merely attracting students to the institutional culture of education itself. The conclusion is that increasing female enrollment is not enough; the educational environment that produces belonging, retention, and professional prospects must also be transformed.

In the field of professional qualification and university outreach programs, the studies by Landerdahl and colleagues occupy a central position. Landerdahl et al. (2011) describe the linkage among university, health, citizenship, and technical training in construction as an instrument for consolidating public policies for women. Landerdahl et al. (2013) show that technical qualification associated with health and citizenship strengthened self-esteem, autonomy, and perceptions of capability among women historically excluded from the sector, although only some of them achieved effective entry into the labor market. In Landerdahl, Padoin, and Villela (2015), economic autonomy appears as an important but insufficient dimension of empowerment, since occupational participation does not automatically eliminate the sexual division of labor or guarantee collective power.

In construction trades, studies on apprenticeship and pre-apprenticeship are particularly revealing. Adah, Daniel, and Tunji-Olayeni (2024) show that Nigerian women seek apprenticeship programs because of their interest in skills, employment, certification, and entrepreneurship, but face nonpayment of stipends, shortages of tools, distance, discrimination, and a fragile transition to work. Wagner and Kulwiec (2022), in turn, show that pre-apprenticeship programs in the United States can improve women's recruitment and retention in the construction industry by combining technical training with social support, mentoring, childcare, transportation, and partnerships with unions and companies. Comparison of the two studies suggests that qualification produces consistent effects only when accompanied by an institutional infrastructure for labor-market integration and support.

Table 3 summarizes recurring education and qualification modalities identified in the studies, as well as their main bottlenecks in the transition to work. The comparison is relevant because it shows that the problem lies not only in the availability of courses, but in the way such provision is connected, or not, to employment networks, social protection, mentoring, and professional recognition.

Table 3 – Education and qualification modalities and their main bottlenecks in the transition to work

Modality	Support/resources	Main bottleneck	Studies
Engineering curriculum	Equality committee; faculty training; protocols	Low institutionalization and visibility	Zapata and Truyol (2022)
University outreach programs	Technical training; health; citizenship	Limited formal employment after the course	Landerdahl et al. (2011; 2013)
Trade apprenticeship	Certification; stipends; kits	Nonpayment; limited labor-market integration	Adah, Daniel, and Tunji-Olayeni (2024)
Pre-apprenticeship	Mentoring; transportation; childcare; union networks	Unequal access and discriminatory culture	Wagner and Kulwiec (2022)
Solidarity economy	Incubation; self-management; institutional support	External dependence; leadership conflicts	Jorge, Borges, and Bortolaso (2024)
Mutual-aid housing construction	Practical learning; collective agency	Work overload and low formalization	Fertrin and Velho (2010)

5.2. From qualification to retention: transition as a central problem

The transition between education and employment is far from linear. In several cases, qualification produces important subjective and technical gains, but does not automatically translate into formal employment, progression, or stability. Landerdahl et al. (2013) report that, among 38 qualified women, only five entered the construction industry. Adah, Daniel, and Tunji-Olayeni (2024) observe that many Nigerian apprentices completed their training without finding structured professional trajectories. Jorge, Borges, and Bortolaso (2024) show that even initiatives based on self-management and the solidarity economy remain dependent on external support and face internal leadership conflicts, low educational attainment, and persistent vulnerability.

The bottlenecks in this transition include both objective and symbolic factors. Objective factors include the absence of hiring networks, union selectivity, lack of support for caregiving and transportation, and scarcity of employer policies for workforce integra-

tion (Wagner; Kulwiec, 2022; Adah; Daniel; Tunji-Olayeni, 2024). Symbolic factors include distrust of women's technical capabilities, a tendency to assign women stigmatized tasks, and difficulty legitimizing their competencies in masculinized environments (Silva; Osterne, 2014; Romcy; Brites, 2015; Macedo et al., 2024). For this reason, retention must be treated as a problem distinct from entry: attraction without retention and progression does not alter the structural pattern of the sector.

Qualification is, therefore, a necessary but insufficient condition for women's inclusion in the construction industry. Without hiring networks, retention support, professional recognition, and efforts to confront organizational biases, training programs tend to produce important subjective and technical gains but limited results in terms of stable occupational participation.

5.3. Leadership, recognition, and the limits of individual advancement

Women's advancement to leadership positions exists, but remains marked by isolation, the constant need to prove value, and limited structural transformation of the organizational environment. Macedo et al. (2024) interpret the trajectories of women in steelmaking and construction as empowerment that is often unconscious and individualized. Achievements are perceived as the result of extraordinary personal effort rather than as the effect of collective institutional rearrangements. Milanesi and Brito (2024) identify similar barriers—sexism, initial disbelief, and the need to demonstrate superior preparedness—across multiple sectors, including construction. Ghanbaripour et al. (2023) note that the lack of female mentors and barriers to promotion are part of the attrition mechanism rather than a mere side effect.

This diagnosis is relevant because it prevents celebratory interpretations of female leadership as sufficient evidence of equality. Cases of success may coexist with resistant organizational structures. When a female leader must adapt her behavior to be accepted, when her promotion does not alter the sector's informal rules, and when her trajectory continues to be viewed as exceptional, female leadership risks being incorporated as a symbolic exception that legitimizes the continuity of inequality. This is precisely one of the criticisms made by Macedo et al. (2024), for whom isolated representation does not amount to collective awareness of empowerment.

For this reason, the literature tends to defend female leadership not only as a desirable outcome, but as a mechanism for transforming sectoral culture. Mentoring, support networks, institutional visibility, promotion to decision-making positions, and accountability of senior management appear as recurring strategies so that leadership ceases to

be a rare event and becomes a driver of work reorganization (Stamarski; Son Hing, 2015; Ghanbaripour et al., 2023; Medina Filho et al., 2024).

6. INSTITUTIONAL POLICIES, GOVERNANCE, AND INTERFACES WITH SDG 5

6.1. Regulatory frameworks, targets, and institutionalization of equality

The gender-equality agenda in the construction industry depends on coordination among organizational culture, public policies, and formal governance mechanisms. In this respect, SDG 5 functions less as a slogan than as a reference for organizing priorities, targets, and responsibilities. Amaral and Peixoto (2021) argue that Target 5.5, aimed at women's full and effective participation at all levels of decision-making, can only be understood in light of the social, economic, and cultural inequalities that restrict women's time, income, and access to spaces of power. Andrade (2022) argues that the Brazilian legal system provides an important but insufficient basis, on its own, for achieving SDG 5. The combination of rules, integrated policies, and cultural change is presented as a condition for formal rights to become substantive equality.

In the construction industry, operationalizing SDG 5 requires that broad equality targets be translated into concrete sectoral practices, such as indicators of female participation by function and hierarchical level, monitoring of wage differences, transparent promotion criteria, anti-harassment protocols, adaptation of PPE, revision of working hours, and retention policies following maternity. In this way, SDG 5 ceases to function solely as a broad normative reference and begins to guide verifiable instruments of organizational governance.

The field-specific literature shows that generic diversity policies or institutional declarations of support for equality are insufficient when there is no redefinition of HR criteria, revision of tacit norms, monitoring mechanisms, or consequences for noncompliance. Stamarski and Son Hing (2015) offer a particularly useful model by demonstrating that organizational structures, human-resource practices, and managerial sexism can reproduce inequalities even in environments that present themselves as meritocratic. Ghanbaripour et al. (2023) reach a similar conclusion when they argue that policies focused on attraction without transformation of gendered practices are inadequate.

In the Brazilian context, articles focused on SDG 5 and public institutions reinforce the importance of institutionalization. Silva and Lima (2022) show that the Judiciary developed specific policies, such as incentives for women's participation, recommendations for gender-balanced composition of examination boards and committees, and the use of indicators for monitoring. Santos and Prado (2024) emphasize the need for sys-

tematic monitoring of indicators to assess the effective achievement of SDG 5 in the country. Candido and Canguçu (2021) also associate the issue with formal policies, but suggest that persistent wage and leadership inequalities signal the insufficiency of initiatives when they are not connected to deeper changes in the world of work.

The construction industry can draw two central lessons from this body of literature. The first is that gender equality must be institutionalized through clearly defined rules, protocols, indicators, and responsibilities. The second is that such institutionalization produces effects only when accompanied by contestation in the domains of culture, language, allocation of time, and revision of informal hierarchies. In this light, SDG 5 should be understood as a governance reference rather than merely as sectoral rhetoric.

6.2. Committees, diversity, metrics, and organizational change

There are also concrete examples of institutional arrangements capable of driving change, although only partially. Medina Filho et al. (2024), in a case study of SESC RJ (Serviço Social do Comércio, a Brazilian nonprofit social services institution, Rio de Janeiro unit), show the potential of diversity committees and affinity groups to review internal rules, support talent retention, and consolidate the inclusion agenda. Although the study is not centered on the construction industry, its analytical usefulness is high because it addresses precisely the problem of governance: how to transform diversity from a topic into a continuous institutional agenda endowed with actors, routines, and internal legitimacy. Santos (2023), in reflecting on diversity and inclusion in the Brazilian construction industry, argues that codes of conduct, strategic diversity management, and affirmative policies are relevant not only for ethical reasons, but also for their effects on innovation and competitiveness.

However, these instruments have limited reach when they are not accompanied by metrics and support from senior leadership. Medina Filho et al. (2024) note the need for stronger institutional support and clear impact indicators. Achon et al. (2024) highlight the absence of structured public policies and limited emphasis on leadership positions. Ghanbaripour et al. (2023) warn that increasing the number of women without transforming the work system can generate frustration and attrition. In other words, governance without monitoring becomes symbolism; monitoring without cultural change becomes bureaucracy.

Table 4 summarizes recurring institutional instruments identified in the studies and their interfaces with SDG 5. The purpose is not to propose a single prescription, but to show that the literature already offers a consistent repertoire of mechanisms combining prevention, correction, education, accountability, and cultural change.

Table 4 – Institutional arrangements and interfaces with SDG 5 identified in the studies

Arrangement	Immediate objective	Interface with SDG 5	Studies
Legal frameworks and public policies	Prohibit discrimination and expand protection	Targets 5.1, 5.2, and 5.c	Andrade (2022); Amaral and Peixoto (2021); Silva and Lima (2022)
Committees and affinity groups	Change culture and revise internal practices	Target 5.c and institutional governance	Medina Filho et al. (2024); Santos (2023)
Mentoring and leadership promotion	Increase retention and progression	Target 5.5	Ghanbaripour et al. (2023); Macedo et al. (2024)
Anti-discrimination protocols	Prevent harassment and provide an institutional response	Targets 5.1 and 5.2	Zapata and Truyol (2022); Ferrari, Cabral, and Salhani (2020)
Metrics and monitoring	Track representation and inequality	Target 5.c	Santos and Prado (2024); Candido and Canguçu (2021)
Technology and work redesign	Reduce risks and expand inclusion	SDG 5 in interface with SDGs 8 and 9	Al Salaheen et al. (2024); Serra and Maia (2021)

A particularly relevant aspect is the cross-cutting potential of the agenda. Leal Filho et al. (2023) argue that gender equality must be promoted in conjunction with other SDGs, including education, decent work, reduced inequalities, and stronger institutions. In the construction industry, this means that the gender agenda should not be confined to human resources. It must extend to construction planning, workplace design, hiring, training, suppliers, reporting channels, PPE procurement, corporate governance, and relations with communities. When the agenda is confined to an administrative department, it tends to lose transformative capacity.

7. INTERSECTIONALITIES AND CONTEXTUAL VARIATIONS

7.1. Class, territory, and social vulnerability

One of the most consistent criticisms concerns the inadequacy of approaches that treat "women" as a homogeneous group. Although many studies still do not develop a robust intersectional analysis, the body of evidence itself reveals that gender inequality intensifies or is reconfigured when intersects with with social class, territory, type of occupational participation, age, motherhood, and race. In several cases, women's entry into

the construction industry is associated with unemployment, poverty, low educational attainment, and an urgent search for economic autonomy, particularly in experiences involving professional qualification, mutual-aid housing construction, the solidarity economy, and work programs (Fertrin; Velho, 2010; Landerdahl et al., 2013; Landerdahl; Padoin; Villela, 2015; Jorge; Borges; Bortolaso, 2024).

Social class appears as a decisive marker because it determines not only the likelihood of entry, but also the type of position occupied within the sector. Romcy and Brites (2015) show a clear distinction between female engineers and architects, on the one hand, and women working in cleaning and food services, on the other. Silva and Osterne (2014) highlight the vulnerability of women working through outsourcing arrangements or concentrated in laborer positions. Ferreira (2023) draws attention to the historical trajectories of Black and mixed-race (parda) women in precarious and undervalued occupations. These differences indicate that the debate on women in the construction industry cannot be conducted solely from the perspective of higher-prestige professions, at the risk of erasing the most precarious and vulnerable segment of the female workforce.

Territory also matters. Studies conducted in the interior of Rio Grande do Sul, Fortaleza, Canoas, Campinas, Nigeria, Malaysia, and Australia show that similar barriers take different forms. What varies is the institutional infrastructure, the local labor market, union strength, regional culture, the availability of training, and existing public policies (Silva; Osterne, 2014; Ghanbaripour et al., 2023; Adah; Daniel; Tunji-Olayeni, 2024; Al Salaheen et al., 2024; Jorge; Borges; Bortolaso, 2024). This contextual variation precludes simplistic universal solutions. What is decisive in one context may be insufficient in another. In locations with limited transportation and family support, for example, retention may depend on stipends and basic logistical support. In more formalized labor markets, the challenge may be concentrated more heavily on hierarchical progression and organizational culture.

7.2. Race, motherhood, age, and other markers

Motherhood repeatedly appears as a marker of inequality. Macedo et al. (2024) show that career breaks for childcare continue to be poorly understood by leadership. Romcy and Brites (2015) report motherhood as a factor in dismissal or restricted opportunities. Ghanbaripour et al. (2023) identify rigid working hours and work-family conflict as important mechanisms of attrition. These findings suggest that the sector still operates with an ideal-worker model detached from caregiving responsibilities, which particularly penalizes women of reproductive age or those responsible for unpaid domestic work.

Age also appears as a marker, although it is less theoretically developed. Milanesi and Brito (2024) report ageism and skepticism toward younger women in leadership positions. Jorge, Borges, and Bortolaso (2024) describe a group composed mostly of women over 50 seeking self-management in construction in a context of vulnerability. These cases indicate that gender inequality does not affect all women identically across the life course. Younger women may face skepticism due to presumed inexperience; older women may experience exclusion due to a restricted labor market and cumulative educational disadvantage.

Regarding race, the studies are uneven. Some neglect it entirely, which is itself a relevant finding. Others address it incisively. Amaral and Peixoto (2021) associate the burden of domestic work with regional and racial inequalities. Diotto and Costa (2023) connect violence, poverty, and racism. Cunha, Almeida, and Machado (2022) show greater victimization and underreporting among Black women during the pandemic. Ferreira (2023) recognizes that inequality in the construction industry is intensified for Black and mixed-race (parda) women. Landerdahl et al. (2013) report racial diversity among women undergoing qualification in a context of unemployment. Despite these advances, the overall conclusion is that intersectionality still occupies a secondary place in much of the sectoral literature.

Table 5 summarizes the main intersectional markers identified in the studies and their effects on women's entry, retention, and progression in the construction industry. Its relevance lies in showing that universal gender policies, when inattentive to class, territory, race, motherhood, and age, tend to benefit only specific segments of the female population.

Table 5 – Recurring intersectional markers and their effects in the construction industry

Marker	Observed effects	Highlighted contexts	Studies
Class and income	Entry driven by necessity; precarious employment relationships; low formalization	Qualification, solidarity economy, mutual-aid housing construction	Landerdahl et al. (2013); Jorge, Borges, and Bortolaso (2024); Fertrin and Velho (2010)
Territory	Barriers vary according to infrastructure and the local labor market	Fortaleza, interior of RS, Canoas, Nigeria, Malaysia, Australia	Silva and Osterne (2014); Romcy and Brites (2015); Adah, Daniel, and Tunji-Olayeni (2024); Al Salaheen et al. (2024); Ghanbaripour et al. (2023)

(continued)

(continued)

Marker	Observed effects	Highlighted contexts	Studies
Race	Greater vulnerability and underreporting; increased burden	Brazil and contexts of violence	Amaral and Peixoto (2021); Cunha, Almeida, and Machado (2022); Ferreira (2023)
Motherhood and care	Career penalties; incompatible working hours	Leadership and retention	Macedo et al. (2024); Ghanbaripour et al. (2023); Romcy and Brites (2015)
Age	Skepticism toward younger women; exclusion of vulnerable older women	Leadership and self-management	Milanesi and Brito (2024); Jorge, Borges, and Bortolaso (2024)

Taken together, these findings support methodological and political critique. The gender-equality agenda in the construction industry must abandon the abstraction of the "universal woman" and recognize that the sector produces very different experiences according to social position, stage of the life course, and territorial context. Without this shift, there is a risk of formulating policies that improve the experiences of women who are already relatively integrated while leaving at the margins those who accumulate greater vulnerabilities.

8. FINAL COMMENTS

Gender inequality in the construction industry is a persistent, multidimensional, and institutionally reproduced phenomenon. The chapter has shown that expanded access to education for women has not automatically translated into occupational participation, retention, hierarchical progression, and professional recognition. This mismatch is sustained by a combination of occupational segmentation, the sexual division of labor, masculinized culture, rigid working hours, harassment, ergonomic inadequacy, weak institutional policies, and limited incorporation of intersectional perspectives.

These patterns make it possible to reject two simplifying interpretations. The first is that women's presence will advance spontaneously as more women graduate. The second is that occasional recruitment or diversity programs are sufficient to solve the problem. Such initiatives tend to be insufficient when they fail to address working hours, informal rules, promotion criteria, organizational culture, construction-site safety, equipment adequacy, support for caregiving, and accountability mechanisms.

At the public-policy level, the evidence suggests at least four priority directions. The first is to integrate the gender-equality agenda into sectoral policies on work, qualification, safety, and innovation, rather than treating it as a peripheral issue. The second is

to strengthen training and pre-apprenticeship programs connected to effective employment networks, with support for transportation, caregiving, mentoring, and professional transition. The third is to consolidate institutional mechanisms for preventing and addressing harassment and violence, with reliable channels, active communication, and leadership accountability. The fourth is to build monitoring systems capable of tracking representation, remuneration, progression, turnover, the supervisory positions held by women, and working conditions, aligning these metrics with SDG 5 and other related goals.

At the organizational level, literature is equally clear. Companies and institutions seeking to reduce inequalities cannot limit themselves to declarative policies. Objective revisions of recruitment, promotion, and evaluation criteria are necessary, along with responsible flexibility in working hours; return-to-work plans following maternity leave; expansion of mentoring and female leadership; acquisition of appropriate PPE; use of technologies that reduce risks and eliminate unnecessary barriers; and revision of the informal norms that continue to define who can lead, circulate, and be recognized in the sector.

Future research faces evident gaps. Comparative studies on policy effectiveness need to be expanded, intersectionalities deepened, more data on remuneration and leadership produced, differences among subsectors of the construction industry investigated, and long-term evaluations of qualification and retention programs developed. Evidence is also needed on ergonomics, PPE design, the impacts of technology on women's inclusion, and the transformation of informal construction-site rules. Without such advances, the debate risks oscillating between repeated diagnoses and insufficiently evaluated solutions.

In summary, the construction industry faces not only a deficit in women's presence, but a deficit in institutional reorganization capable of converting presence into sustained and meaningful participation, recognition, and power. The interface with SDG 5 demonstrates that gender equality in the sector is not a supplementary agenda, but a condition for a construction industry that is safer, more innovative, more sustainable, and more socially legitimate.

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CHAPTER 10

Educating engineers for sustainability: educational innovation, SDGs, and transformation in higher education

Heloisa Candia Hollnagel, Ana Paula Branco do Nascimento,
Leon Henrique Martins de Mendonça, António José Guerner Dias

1. INTRODUCTION

Climate change, rapid urbanization, environmental degradation, and growing pressure on natural resources have intensified the need for integrated responses to sustainable development, a concept consolidated in the Brundtland Report (WCED, 1987) and widely discussed in Brazilian literature since the beginning of this century (Veiga, 2006). In this context, the Sustainable Development Goals (SDGs), established by the United Nations, have become a strategic framework for guiding public policies, institutional practices, and educational processes committed to the 2030 Agenda (UN, 2015). In engineering, particularly civil engineering, these challenges are central because its professionals are directly involved in the design, implementation, and management of infrastructure, buildings, urban systems, and other components of the built environment, significantly influencing the environmental, social, and economic impacts of development (Silva; Souza; Leal, 2012; Kibert, 2016; Mangalore et al., 2025).

By integrating environmental, social, and governance (ESG) criteria into management and decision-making, organizations have expanded their role in promoting sustainable development, linking business objectives to global challenges. As a result, the SDGs have gained growing relevance in government, academic, and business agendas, which is reflected, in the corporate sphere, in the rapid growth of the literature on ESG disclosure and its effects on corporate performance (Khan, 2022). Nevertheless, research on the integration of the SDGs into engineering education remains scarce, especially in Brazil. In

this regard, recent studies advocate curricula and active-learning methods that foster sustainability competencies and connect theory and practice (Ramirez-Mendoza et al., 2020; Mahrishi et al., 2025).

The literature emphasizes that incorporating this new paradigm into engineering education requires research that moves beyond conceptual discussions to examine how curricula, pedagogical practices, institutional strategies, and learning processes can be implemented to support education aligned with sustainability challenges (Ramirez-Mendoza et al., 2020; Mahrishi et al., 2025). Consequently, analyzing educational experiences that demonstrate strategies for integrating the SDGs into engineering education has become increasingly relevant.

Against this background, this chapter examines the incorporation of the SDGs into engineering education through the experience of the required *Sustainability in the Built Environment* course (in Portuguese, *Sustentabilidade no Ambiente Construído*) offered in the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu, São Paulo, Brazil. It describes how curriculum design and competency-based pedagogical strategies, including active learning, case studies, seminars, and research-paper development, can help educate engineers who are capable of analyzing and proposing sustainable solutions to infrastructure and urban challenges in accordance with the 2030 Agenda.

2. THE ROLE OF CIVIL ENGINEERING IN ADVANCING THE SDGS

2.1. Theoretical foundations of environmental impacts in the built environment

The built environment holds a strategic position in the 2030 Agenda because it concentrates impacts associated with urbanization, energy consumption, and natural resource use. Civil engineering can reduce these impacts by applying environmental and energy criteria to the planning, construction, and operation of buildings, using the SDGs as a reference for professional practice and education (Tavares, 2006; Silva, 2007; Lamberts; Dutra; Pereira, 2014; Maricato, 2015; UN, 2015).

International reports and studies, such as those published by the Institution of Civil Engineers in the United Kingdom, show that infrastructure and the built environment play a decisive role in achieving the SDGs and require increasingly resilient, efficient, and sustainable solutions (ICE, 2025). Research conducted since the second half of the twentieth century has also shown that emissions associated with construction materials and building operations account for a significant share of global environmental impacts,

reinforcing the importance of tools such as life cycle assessment (LCA) for quantifying and reducing these impacts.

In Brazil, these approaches have been adapted to the characteristics of the national energy mix, construction technologies, and waste-management practices, enabling more accurate assessments of the sector's environmental impacts. Energy efficiency, circular economy, and sustainable urban planning have therefore become complementary strategies for promoting more sustainable cities and reducing the impacts of the construction sector.

Based on this framework, Table 1 summarizes Brazilian and international studies that support an understanding of the main environmental impacts associated with the built environment and the strategies civil engineering uses to mitigate them. These topics also form the conceptual foundation of the *Sustainability in the Built Environment* course and guide the selection of content, case studies, and discussions developed throughout the semester.

Table 1 shows the complementarity of the strategies for mitigating the impacts of the built environment. In the course, this framework guided the selection of seminars, case studies, and SDG-related activities, with real civil engineering problems serving as the organizing focus.

Table 1 – Main environmental impacts of the built environment and civil engineering contributions to sustainability

Topic	Author(s)	Main concept	Contribution to the study
Carbon footprint of the built environment	Pomponi; Moncaster (2018); Silva (2007); Sandanayake; Zhang; Setunge (2017)	Embodied and operational carbon emissions in buildings	Shows that the construction sector is emissions-intensive and presents indicators adapted to the Brazilian context
Global emissions and buildings	IPCC (2022)	Buildings as a key sector in climate mitigation	Scientific basis for global emission-reduction policies
Life cycle assessment (LCA)	Röck et al. (2020); Tavares (2006); Evangelista et al. (2018); Dixit (2017)	Emissions throughout the building life cycle	Integrates a global approach with methods adapted to Brazil
Building energy assessment	Cabeza et al. (2014); Carlo; Lamberts (2008)	Use of LCA and life cycle energy analysis (LCEA) in construction	Methodological framework with practical application in Brazil

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Topic	Author(s)	Main concept	Contribution to the study
Construction and demolition waste	Villoria Sáez; Porras-Amores; Del Río Merino (2020); Angulo et al. (2011); Pinto (1999); Richardson (2013)	Construction and demolition waste management	Combines international practices with foundations established in Brazil
Circular economy in construction	Ajayi et al. (2017); Angulo et al. (2011); Karji; Namian; Tafazzoli (2020); Tafazzoli; Mousavi; Kermanshahi (2020)	Design for deconstruction and material reuse	Connects circular economy with practices previously studied in Brazil
Energy efficiency	Ürge-Vorsatz et al. (2020); Lamberts; Dutra; Pereira (2014)	Nearly zero-energy buildings (nZEB)	Integrates a global concept with Brazilian energy-efficiency standards
Global energy consumption	IEA (2020); Lamberts; Dutra; Pereira (2014)	High energy consumption in the construction sector	Connects global data with national strategies
Urbanization and environmental impact	Seto; Pandey (2019); Maricato (2015)	Urban expansion and socioenvironmental impacts	Connects global urban growth with the Brazilian context
Sustainable cities	Bibri; Krogstie (2017); Rolnik et al. (2015)	Smart and sustainable cities	Integrates urban technology with Brazilian social analysis

2.2. Changes in engineering education

Universities play a strategic role in advancing sustainable development by connecting professional education, knowledge production, and engagement with society. However, they still face challenges in integrating the environmental, social, and economic dimensions of sustainability into educational processes in a balanced manner (Mohd et al., 2024; Aung; Hallinger, 2026). Incorporating the SDGs into engineering curricula offers an opportunity to align academic education with contemporary societal demands while advancing the transformation of engineering education through competency-based approaches and pedagogical innovation consistent with the 2030 Agenda (UN, 2015; Leal Filho et al., 2018; Denissova et al., 2026).

The literature shows that sustainability is still incorporated into higher education in a fragmented manner, highlighting the need for more integrated curricula and stronger connections among teaching, research, and community outreach. Key competencies in this process include systems thinking, interdisciplinarity, socioenvironmental responsibility, and the ability to address complex problems, all of which are considered essential to contemporary engineering education (Allen et al., 2006; Allenby et al., 2009; Wals,

2011; Lozano et al., 2017; Desha; Rowe; Hargreaves, 2019; Beagon et al., 2023; Zanitt et al., 2022).

Research also shows that this curricular transformation involves a gradual shift from content-delivery models toward approaches focused on competency development and active learning (Córdova-Esparza et al., 2024).

Methods such as problem-based learning, project-based learning, applied research, and interdisciplinary approaches, including STEAM, connect theory and practice and help prepare professionals to work in complex, sustainability-oriented contexts (Ekayana et al., 2024).

Recent studies also show that perceptions of the SDGs vary according to social, economic, and territorial factors. In an analysis of different Italian regions, Foroudi et al. (2025) found high public awareness of sustainability but substantial regional inequalities in the perceived impacts of the SDGs, indicating that public policies and regional contexts directly shape this process. The authors also call for further research in university settings, particularly in strategic fields such as urban planning and engineering.

Against this background, Table 2 brings together publications from 2017 to 2026 that summarize the main contributions of the literature on sustainability integration and new pedagogical strategies in engineering education. These sources informed the instructional planning of the *Sustainability in the Built Environment* course, guiding the selection of teaching methods, thematic seminars, and student activities.

Table 2 – Competencies, active-learning methods, and sustainability in engineering education

Topic	Reference	Main contributions	Thematic area
Engineering competencies	Beagon et al. (2023).	Highlights systems thinking and interdisciplinarity.	*Professional competencies*
Competencies and holistic education	Silva; Teixeira (2022).	Integrates technical, social, environmental, and humanistic competencies.	
Competencies and the labor market	Huesca et al. (2024).	Highlights leadership, critical thinking, and teamwork.	
Lifelong learning	Van den Broeck et al. (2024).	Continuous learning as a requirement for engineers.	
Interdisciplinary competencies	Allvin et al. (2020).	Reinforces interdisciplinary collaboration.	
Engineering and Industry 4.0	Jamila (2020).	*Soft skills and autonomy in the digital context.*	

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Topic	Reference	Main contributions	Thematic area
Digital literacy and competencies	Wang; He (2022).	Systematizes trends in knowledge, skills, attitudes, and capabilities, including critical and creative uses of technology in higher education.	*Professional competencies*
Structured sustainability competencies	Castellanos; Queiruga-Dios; Álvarez (2021).	Need for structured curricular integration.	
Sustainability in engineering	Desha; Rowe; Hargreaves (2019).	Identifies gaps in sustainability education.	*Sustainability and SDGs*
Education for sustainability	Lozano et al. (2017).	Integrates competencies and Education for Sustainable Development (ESD).	
Engineering and sustainability	Raoufi et al. (2019).	Active learning improves understanding of sustainability.	
Curriculum and sustainability	Sánchez-Carracedo et al. (2021).	Engineering shows greater progress in sustainability competencies.	
Sustainability in undergraduate education	Leal Filho et al. (2018).	Higher education as an agent of transformation.	
Sustainability in the curriculum	Zanitt et al. (2022).	Still limited integration in engineering programs.	
Engineering and the SDGs	Mahrishi et al. (2025).	Connects engineering education with the SDGs.	
Triple Bottom Line	Elkington (1997); Aung; Hallinger (2026).	Greater progress in the environmental dimension and less in the economic dimension.	
Experiential learning	Miranda et al. (2020).	PBL develops professional competencies.	*Experiential learning*
Learning by doing	Rathi; Nirgude (2022).	Hands-on learning improves performance.	
Experiential learning	Tembrevilla; Phillion; Zeadin (2024).	Increases engagement and retention.	
Design-based teaching	Ansaf; Jaksic (2019).	Develops critical thinking.	
Research-based learning	Noguez; Neri (2019).	Develops critical thinking and research skills.	
Experiential learning	Khoshabeh; Gilja (2021).	Improves employability and problem-solving.	

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Topic	Reference	Main contributions	Thematic area
Engineering design and STEM competencies	Kim; Oliver; Kim (2019).	Develops creative and systematic thinking, problem-solving, collaboration, and knowledge integration.	*Experiential learning*
Active-learning methods	Córdova-Esparza et al. (2024).	Increases engagement and meaningful learning.	*Active learning and PBL*
Active-learning methods	Kannan et al. (2020); Awwad (2025).	Improves academic performance.	
STEAM active-learning methods	Ekayana et al. (2024).	Stimulates creativity and innovation.	
Flipped classroom	Priyaadharshini; Vinayaga Sundaram (2018).	Develops critical thinking.	
Flipped learning and competencies	Amado-Moranchel; Sayeg-Sánchez (2023).	Develops argumentation skills.	
Flipped learning and soft skills	Lang et al. (2018).	Improves leadership and communication.	
Active-learning methods (engineering)	Reis et al. (2023).	Global growth of active-learning methods.	
Curriculum and methods	Knowles; DeCoito (2020).	Integrates student-centered learning.	
Pedagogical trends	Maladzhi; Kanakana-Katumba (2020); Matos Junior; Francisco; Matos (2020); Martín-Garín et al. (2021).	PBL and competency-based learning predominate; PBL and RBL are effective for sustainability.	
Service-learning	López-Santiago et al. (2024).	Develops social and environmental competencies.	*Other*
Faculty competencies	Neves et al. (2021).	Need for faculty pedagogical development.	

Note: STEAM = science, technology, engineering, arts, and mathematics; PBL = *Problem-Based Learning*; RBL = research-based learning; service-learning = community-engaged learning.

Several of these approaches guided the course activities, which combined interactive lectures, seminars, case studies, and the development of a research paper. Among them, learning by doing is particularly important and is discussed in the next section.

2.3. Competency-based learning and active approaches: *learning by doing*

The principle of learning by doing has become one of the central tenets of contemporary engineering education because it promotes active, contextualized learning oriented toward solving real-world problems (Ramirez-Mendoza et al., 2020; Rathi; Nirgude, 2022). By connecting theory and practice, this approach supports the development of technical, cognitive, and socioemotional competencies required in complex contexts and has increasingly been incorporated into engineering education, including in Brazil (Matos Junior; Francisco; Matos, 2020).

Learning by doing is aligned with competency-based education and helps address the demands of an increasingly complex and multidimensional built environment. Essential competencies include systems thinking, critical analysis, decision-making under uncertainty, and interdisciplinary practice (Desha; Rowe; Hargreaves, 2019). Incorporating environmental and energy criteria into education also reinforces the need to prepare engineers who can understand environmental impacts throughout the life cycle of buildings (Tavares, 2006; Lamberts; Dutra; Pereira, 2014).

This orientation is also reflected in models such as outcome-based education (OBE), which aligns learning objectives, pedagogical strategies, and outcome assessment (Sánchez-Carracedo et al., 2021; Mahrishi et al., 2025). By prioritizing evidence of learning in concrete situations, this perspective brings education closer to professional practice and is consistent with Brazil's National Curriculum Guidelines for Engineering Programs, which emphasize competency development and the solution of societal problems (Brasil, 2019).

Despite these advances, difficulties remain in translating the competencies prescribed in curricula into competencies actually developed during the educational process. According to Mulder (2017), this process still faces methodological and institutional challenges. In Brazil, structural limitations and regional inequalities make implementation even more complex, requiring stronger connections among educational policies, teaching practices, and the demands of society and industry. The challenge is not unique to Brazil: in other resource-constrained contexts, structural barriers prevent graduates from applying their technical knowledge (Kyaw, 2020).

In this context, a conception of engineering education grounded in lifelong learning, interdisciplinarity, and innovation has been gaining ground, preparing professionals to respond to rapid technological and socioenvironmental change (Allvin et al., 2020; Van den Broeck et al., 2024). The SDGs broaden this role by positioning engineers not only as technical problem solvers but also as agents of environmental, social, and economic transformation (Leal Filho et al., 2018; Mahrishi et al., 2025).

2.4. Integrating the SDGs into engineering education

Based on the literature reviewed, Table 3 systematizes the main pedagogical and institutional barriers to integrating the SDGs into engineering education. These include curricular fragmentation, limitations in faculty development and competency assessment, and insufficient connections among teaching, research, and professional practice. This synthesis clarifies the different levels at which these difficulties arise.

Table 3 – Main difficulties in integrating the SDGs into engineering education

Challenge	Evidence identified	Authors	Expected educational response
Curricular fragmentation	Sustainability appears in isolated courses without cross-curricular integration	Desha; Rowe; Hargreaves (2019); Miñano Rubio et al. (2019); Sabri (2025)	Supports treating sustainability as an organizing focus rather than a peripheral topic
Predominance of the traditional technical paradigm	Education prioritizes calculation, design, and technical efficiency, with limited socioenvironmental discussion	Sabri (2025); Mulder (2017); Desha; Rowe; Hargreaves (2019)	Reinforces the need to transform engineering education
Limited interdisciplinarity	Programs still operate in disciplinary silos, hindering SDG integration	Zelinka; Amadei (2017); Ramirez-Mendoza et al. (2020); Sabri (2025)	Supports understanding the built environment as a complex system
Difficulty translating SDGs into assessable competencies	Sustainability is not easily converted into measurable learning outcomes	Desha; Rowe; Hargreaves (2019); Mahrishi et al. (2025); Miñano Rubio et al. (2019)	Supports competency-based assessment and applied activities
Limited faculty development	Faculty face difficulties in applying sustainability	Desha; Rowe; Hargreaves (2019); Matthew et al. (2023); Mahrishi et al. (2025)	Supports faculty development and collaborative planning
Overloaded curricula	Sustainability competes with traditional technical content	Matthew et al. (2023); Desha; Rowe; Hargreaves (2019)	Supports cross-curricular integration rather than isolated courses
Limited connection with real-world problems	Learning remains abstract and disconnected from real-world challenges	Ramirez-Mendoza et al. (2020); Mahrishi et al. (2025); Sabri (2025)	Supports using the course as an applied laboratory

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Challenge	Evidence identified	Authors	Expected educational response
Difficulty measuring educational impact	Few studies assess long-term outcomes	Mahrishi et al. (2025); Ragadhita et al. (2026)	Indicates the course's potential as an evaluative case study
Institutional resistance to change	Curricular reforms depend on organizational culture and accreditation	Desha; Rowe; Hargreaves (2019); Mahrishi et al. (2025); Sabri (2025)	Reinforces the role of institutional decision-making in curriculum innovation
Limited integration among teaching, research, and practice	Sustainability requires connections between academic education and professional practice	Ramirez-Mendoza et al. (2020); Purcell; Henriksen; Spengler (2019); Desha; Rowe; Hargreaves (2019)	Supports the course as a bridge between research and practice

Table 3 provides the framework for examining, in the next section, the extent to which the course responds to the limitations identified in the literature.

3. THE *SUSTAINABILITY IN THE BUILT ENVIRONMENT* COURSE AS A STRATEGY FOR INTEGRATING THE SDGS

3.1. Learning objectives and alignment with the SDGs

Universities are strategically important to sustainable development but still face difficulties in integrating its environmental, social, and economic dimensions into education (Mohd et al., 2024; Aung; Hallinger, 2026). Incorporating the SDGs into engineering curricula can help reduce this fragmentation by connecting teaching, research, and community outreach while developing competencies such as systems thinking, interdisciplinarity, socioenvironmental responsibility, and complex problem-solving (UN, 2015; Lozano et al., 2017; Leal Filho et al., 2018; Desha; Rowe; Hargreaves, 2019; Beagon et al., 2023; Zanitt et al., 2022).

In response to this challenge, the *Sustainability in the Built Environment* course was designed to integrate the SDGs into the education of master's students by combining theoretical foundations, active-learning methods, and practical application. The specific objectives stated in the course syllabus are to:

- Develop a critical understanding of sustainability challenges in the built environment, with an emphasis on the SDGs and the targets of the 2030 Agenda.

- Update students' knowledge of analytical, assessment, and intervention tools, enabling the integrated application of these concepts in research and professional practice.
- Develop competencies for applying acquired knowledge through critical analysis of case studies and the proposal of sustainable solutions in civil engineering.

These objectives are pursued through a combination of interactive lectures, active-learning methods, case studies, thematic seminars, and research-paper development. Rather than merely delivering content, the course creates learning situations in which students analyze real-world problems, build evidence-based solutions, and develop competencies aligned with the SDGs.

3.2. Curriculum structure and content organization

The course curriculum is organized around four integrative areas: (i) foundations of sustainability and the Sustainable Development Goals; (ii) urban planning and sustainable construction; (iii) green infrastructure, climate change, and resilience; and (iv) sustainability indicators. This organization supports a systemic approach to civil engineering by connecting theoretical foundations, methods, and professional applications.

The syllabus is aligned with recent literature on engineering education, which advocates integrating environmental, urban, and technological considerations into professional education (Zelinka; Amadei, 2017). The inclusion of LCA, environmental certifications, low-carbon buildings, and *net-zero* construction also connects the course to current international discussions on sustainability in the built environment.

Given the challenges posed by climate change and the growing frequency of extreme events, civil engineering plays a strategic role in reducing carbon emissions, using natural resources efficiently, and developing more resilient infrastructure. These themes run throughout the course, connecting technical knowledge with the environmental, social, and economic dimensions of sustainability.

3.3. Teaching methods and student-centered active learning

Consistent with the course objectives, the pedagogical strategy combines interactive lectures, critical reading of research articles, case studies, thematic seminars, and collaborative activities. These methods encourage students to take an active role in learning, supporting collective knowledge construction and the development of analytical, research, and professional competencies (Desha; Rowe; Hargreaves, 2019; Ragadhita et al., 2026).

The activities were designed according to the principles of experiential learning, learning by doing, and problem-based learning (PBL), connecting theory and practice through real-world built-environment problems. Individually, students conducted critical readings and literature analyses; in groups, they developed case studies and seminars and proposed solutions to SDG-related challenges, fostering intellectual autonomy, collaborative work, and interdisciplinarity. Seminars and oral presentations also developed scientific communication, argumentation, critical-thinking, and synthesis skills essential to twenty-first-century engineering practice.

Peer discussion broadened the learning process by encouraging the exchange of perspectives and the continuous improvement of proposals until the research paper, the course's final product, was submitted at the end of the semester.

3.4. Assessment strategies and competency development

The course assessment process was designed to emphasize the application of knowledge to real-world situations, combining practical activities (70%) and the research paper (30%). This structure is aligned with competency-based education, in which student performance is assessed through the ability to mobilize knowledge, skills, and attitudes to analyze and propose solutions to built-environment problems (Mahrishi et al., 2025).

Each master's student developed a research paper related to their line of research, either individually or in groups of two or three, thereby connecting teaching, research, and professional practice. In addition to consolidating classroom content, this activity supported the development of research competencies, critical thinking, and applied analytical skills while strengthening academic supervision. This strategy is also consistent with experiential and transformative learning, which can promote cognitive and behavioral changes among students (Tembrevilla; Phillion; Zeadin, 2024; Mangalore et al., 2025).

The 21 papers analyzed were produced in two offerings of the course, in 2024 and 2025, involving approximately 40 students. The chapter authors subsequently conducted a document analysis and classified each paper by research topic, course area, and competencies mobilized. Two authors classified the papers independently and compared their assessments in a consensus meeting to resolve disagreements. This analysis identified thematic trends and clarified how the course connected civil engineering content with the SDGs, as shown in Table 4.

Table 4 – Research projects developed in the course (final product: research paper)

#	Paper topic	Course area	Competencies mobilized	Relationship to the SDGs
1	Sustainable urban drainage and the 2030 Agenda	Sustainable urban infrastructure	Systems thinking, environmental analysis	SDGs 6, 11, 13
2	Diagnostic engineering and accessibility	Sustainability and inclusion	Social responsibility, technical analysis	SDGs 10, 11
3	*Lean Construction* and the SDGs	Construction management	Efficiency, collaborative work	SDGs 9, 12
4	Technological control of concrete	Materials and technology	Technical rigor, innovation	SDG 9
5	Facade maintenance	Building pathology and durability	Critical analysis, prevention	SDGs 11, 12
6	Solid-waste policy in construction	Waste management	Critical thinking, sustainability	SDGs 11, 12
7	Glass-fiber-reinforced concrete	Sustainable materials	Innovation, performance analysis	SDGs 9, 12
8	Structural pathologies in risk areas	Geotechnical engineering	Technical diagnosis, risk analysis	SDGs 11, 13
9	Carbon reduction in construction	Sustainability and climate	Environmental analysis, decision-making	SDG 13
10	Construction on steep terrain	Sustainable urban planning	Problem-solving, adaptation	SDGs 6, 11, 13
11	Foundation pathologies	Structural engineering	Technical analysis, investigation	SDGs 11, 12
12	Nature-based solutions (NbS)	Green infrastructure	Interdisciplinarity, innovation	SDGs 6, 11, 13
13	Sanitation systems and sustainability	Sanitation	Critical thinking, systems analysis	SDG 6
14	Pavements containing tire waste	Circular economy	Sustainability, innovation	SDGs 11, 12
15	CO_2 inventory and offsetting	Environmental engineering	Environmental analysis, planning	SDGs 11, 13
16	Low-carbon construction solutions	Sustainability and innovation	Strategic thinking	SDGs 12, 13
17	Urban gardens and rainwater harvesting	Urban green infrastructure	Interdisciplinarity, sustainability	SDGs 2, 6, 11
18	Friction in concrete floors	Structural engineering	Technical analysis, modeling	SDG 9

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#	Paper topic	Course area	Competencies mobilized	Relationship to the SDGs
19	Pavement and the 2030 Agenda	Road infrastructure	Urban planning, critical analysis	SDGs 9, 11
20	Open spaces and urban sustainability	Urban planning	Territorial management, social participation	SDG 11
21	Pathologies in facade mortars	Materials and durability	Technical analysis, prevention	SDG 12

The papers presented in Table 4 show that the range of topics investigated connected real civil engineering problems with the SDGs, spanning construction materials and technologies, urban planning, green infrastructure, and carbon-emission reduction. This diversity indicates that sustainability was treated not as an isolated topic but as a cross-cutting element across civil engineering fields. In a study of 256 students from 30 countries, Picatoste et al. (2025) found high levels of concern for sustainability principles, shaped by individual and sociocultural characteristics. Their findings reinforce the important role of higher education in professional preparation for achieving the 2030 Agenda. This thematic distribution is summarized in Figure 1.

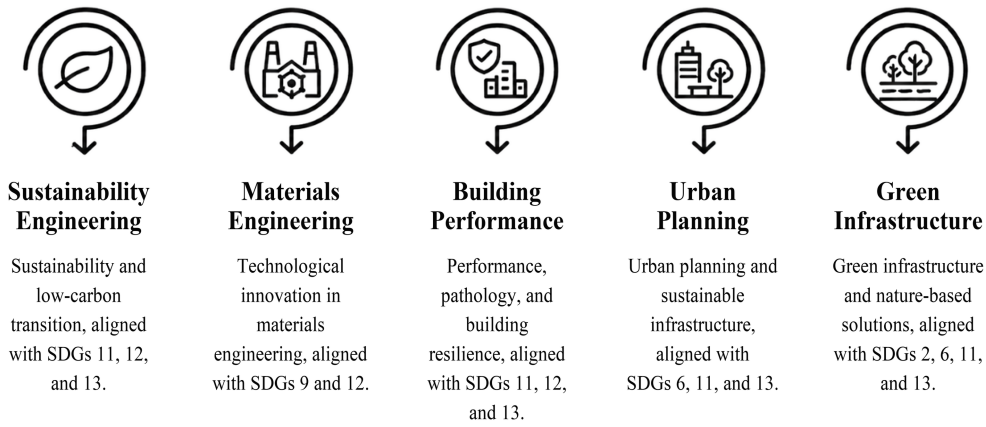


Figure 1 – Thematic clusters of papers developed in the *Sustainability in the Built Environment* course, showing the integration of professional competencies, applied research, and the SDGs.

3.5. Connection with the built environment and practical application

The papers show that the master's students applied course content to concrete built-environment problems. Organized into the areas of materials, building perfor-

mance, urban infrastructure, territorial planning, and nature-based solutions, they reflect an expansion from a technical focus toward systemic and interdisciplinary analyses.

SDGs 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), and 13 (Climate Action) predominated, with additional contributions related to SDGs 2, 6, 9, and 10. This distribution shows that the studies extended from technological innovation and building performance to durability, resilience, and urban integration.

The thematic distribution indicates that sustainability functioned as a cross-cutting focus of the course and broadened civil engineering's engagement with environmental, social, and technological challenges (Figure 1).

The results summarized in Figure 1 indicate that the course brought together technical, systemic, and interdisciplinary approaches to built-environment problems. The analysis is cross-sectional rather than longitudinal: the clusters describe the thematic distribution of the set of papers, not a change across the two course offerings. The experience therefore addresses some of the difficulties identified in Table 3, particularly curricular fragmentation, limited connections with real-world problems, and weak integration among teaching, research, and professional practice.

3.6. Future perspectives and pathways for transformation

Higher education plays a strategic role in educating engineers committed to sustainability (Sabri, 2025; Denissova et al., 2026). The experience analyzed shows that the SDGs can be explicitly integrated into the educational process. Figure 2 presents the frequency of the SDGs addressed in the papers; a single paper may be associated with more than one goal.

As shown in Figure 2, SDG 11 (Sustainable Cities and Communities) predominated (32.5%), followed by SDG 12 (Responsible Consumption and Production; 20.0%) and SDG 13 (Climate Action; 17.5%). SDGs 6 and 9 each accounted for 12.5% of the associations, whereas SDGs 2 and 10 each represented 2.5%. This distribution indicates that the studies focused primarily on urban planning, green infrastructure, the circular economy, resource efficiency, and carbon-emission reduction, consistent with the course's focus and the challenges of the built environment.

Conversely, the lower frequency of SDGs 2 and 10 indicates that the social dimensions of sustainability were addressed only occasionally, in topics such as urban gardens and social inclusion. This finding provides a useful diagnosis for improving the course and points to opportunities to incorporate equity, social inclusion, environmental justice, and urban governance more systematically.

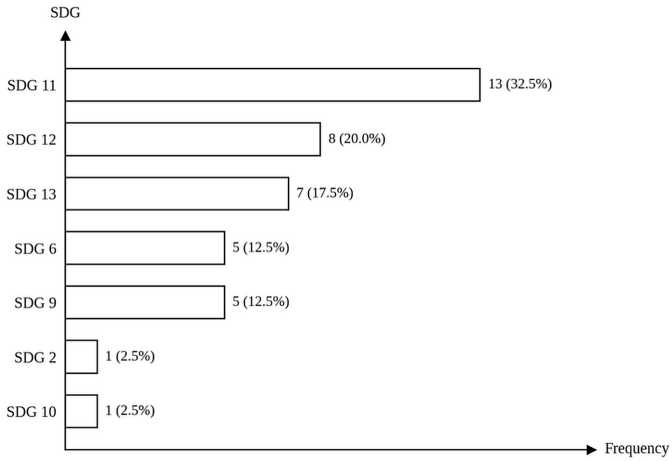


Figure 2 – Frequency of Sustainable Development Goals in the papers developed in the course (a single paper may be associated with more than one SDG).

Together, the thematic clusters and SDG distribution indicate connections among technical competencies, systems thinking, interdisciplinarity, and critical analysis. These results are consistent with literature advocating competency-oriented curricula, active-learning methods, and sustainability as an organizing focus of engineering education (Desha; Rowe; Hargreaves, 2019; Ragadhita et al., 2026).

In addition to demonstrating alignment with SDGs 11, 12, and 13, the results show that the course supports an integrated understanding of the built environment by connecting traditionally technical content with urban planning, sustainability, and climate change. They also reveal the need to strengthen the treatment of sustainability's social dimensions, interdisciplinarity, and dialogue with public policy and governance.

Another relevant aspect is the consolidation of learning grounded in real-world problems. The papers addressed concrete civil engineering challenges, including urban drainage, waste management, energy efficiency, sustainable materials, and infrastructure resilience, enabling students to connect theory, research, and professional practice. This characteristic brings the experience closer to the principles of learning by doing and competency-based education advocated by Zelinka and Amadei (2017).

In light of these results, the course has become a strategy for integrating teaching, research, and professional practice, using the SDGs as an organizing framework for learning and competency development. As shown in Table 4, this approach is reflected in papers that connect different dimensions of civil engineering, from technological innovation to urban sustainability, green infrastructure, and the transition to a low-carbon economy. Consistent with the challenges summarized in Table 3 and the strategies pre-

sented in Table 5, these results indicate that teaching methods centered on competencies and real-world problems play a decisive role in integrating sustainability into engineering education.

Table 5 – Challenges identified in the literature and pedagogical strategies adopted in the *Sustainability in the Built Environment* course

Challenges identified	Evidence observed in this course
Curricular fragmentation	Integration of the SDGs across built-environment areas
Limited connection with real-world problems	Research papers based on concrete civil engineering challenges
Predominantly technical education	Mobilization of environmental, social, and systemic competencies
Limited interdisciplinarity	Topics involving urban planning, green infrastructure, materials, mobility, and climate change
Disconnect between teaching and research	Papers linked to the master's students' lines of research
Difficulty operationalizing the SDGs	Course planning structured around the SDGs and professional competencies

Overall, the results indicate that the presence of the SDGs in the papers developed in the course stems less from specific content than from the way the educational process is organized. The implications of these findings for engineering education, and their limitations, are discussed in the next section.

4. FROM THEORY TO PRACTICE: COURSE CONTRIBUTIONS TO INTEGRATING THE SDGS INTO ENGINEERING EDUCATION

Integrating sustainability into engineering education requires more than adding specific content. The *Sustainability in the Built Environment* course illustrates one way to incorporate the SDGs into graduate civil engineering education through pedagogical strategies linked to contemporary social, environmental, and technological demands. The literature identifies systems thinking, problem-solving, socioenvironmental responsibility, and interdisciplinarity as competencies needed to move beyond models centered exclusively on technical knowledge. In the course, case studies, seminars, and research papers mobilized these competencies in addressing built-environment problems and brought academic education, research, and professional practice closer together. The papers focused primarily

on SDGs 11, 12, and 13, concerning sustainable cities, responsible consumption, and climate action. The lower frequency of socially oriented SDGs nevertheless points to opportunities for curriculum improvement.

The chapter's main contribution is to demonstrate how the SDGs can be operationalized through a structured pedagogical experience. The alignment of learning objectives, course activities, and research output enabled sustainability to be treated as a cross-cutting element across civil engineering fields, consistent with the principles of learning by doing.

Because this experience was developed in a single course within a professional master's program, the results cannot be generalized to other educational contexts. Moreover, the document analysis identifies topics, SDGs, and mobilized competencies but does not directly measure changes in student performance or behavior. Even so, the experience offers elements that may be adapted to undergraduate and graduate programs, provided that their institutional and pedagogical characteristics are respected.

Transforming engineering education requires curriculum innovation, faculty development, interdisciplinarity, and engagement with concrete societal issues. Sustainability-focused courses can stimulate broader changes when they are integrated into the program curriculum and connected with other curricular components. The experience contributes to the debate on incorporating the SDGs into engineering education and points to pathways for building a more sustainable, resilient, and socially inclusive built environment.

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CHAPTER 11

Impact of Engineering I graduate programs on the 2030 Agenda: analysis of alignment with the Sustainable Development Goals based on the 2021–2023 nationwide study

Carlos Alberto Cioce Sampaio, Lúcio Carlos de Carvalho Boggian, Enio Ricardo Dorvil Coelho, José Carmino Gomes Jr., Cláudia Terezinha Kniess, Arlindo Philippi Junior

1. INTRODUCTION

Discussing the role of graduate education in the 2030 Agenda requires moving beyond conventional readings of academic production and overcoming the narrow view that the impact of science is confined to the "walls of the university." The continuous evaluation of graduate programs is a key policy instrument for steering improvements in the scientific knowledge landscape and advancing technological development in Brazil (Romano et al., 2023). In recent years, the Coordination for the Improvement of Higher Education Personnel (CAPES) has consolidated a paradigm shift in its multidimensional evaluation by introducing the criterion "Impact on Society." This guideline requires programs to demonstrate not only the excellence of their publications but also the real and potential benefits that knowledge generates for the population, public policymaking, and the transformation of territories (Sampaio; Philippi Jr., 2021).

In the Engineering I Evaluation Area, the requirement for real impact and alignment with sustainability is intrinsic to the area and indispensable. The area encompasses branches that developed from civil engineering, including urban, geotechnical, transportation, sanitary, environmental, and water resources engineering. By its very nature, Engineering I brings together research that directly addresses the design of resilient infrastructure, innovations in materials, optimization of production processes, basic sanitation, energy efficiency, mobility, and adaptation to climate change. It is therefore an area whose academic

production inevitably engages with concrete problems in territories and the production system (Brasil, 2022).

The CAPES Engineering I Area Document (2021–2024) emphasizes that the area's activities are closely linked to nearly the entire 2030 Agenda, while highlighting four Sustainable Development Goals (SDGs) with direct impact: SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). In this context, engineering assumes a proactive role in economic and social development, requiring solutions based on complex systems, lateral thinking, and knowledge transfer across the social, exact, and environmental sciences (Rahimifard; Trollman, 2018; Brasil, 2021a).

At the same time, a methodological challenge remains: how can the alignment of Engineering I graduate programs with the SDGs be identified systematically, comparably, and nationwide? The mere existence of technological research and patents does not, in itself, guarantee a clear understanding of their social, environmental, and territorial impact. Analytical instruments must be developed to examine themes, concentration patterns, gaps, and trends over time. Developing impact metrics requires moving beyond a purely productivist perspective (Gomes Junior et al., 2023) and calls for the use of advanced scientometric technologies. Recent models have used text mining, computational algorithms based on relational databases, and artificial intelligence—including large language models (LLMs) and machine learning—to analyze large volumes of CAPES open data and databases such as OpenAlex (Sampaio et al., 2025a).

These methodologies were tested and validated through pioneering work in the CAPES Environmental Sciences Evaluation Area, which developed algorithms to associate master's theses and doctoral dissertations with UN descriptors (Sampaio; Philippi Jr., 2021; Gomes Junior et al., 2023; Sampaio; Philippi Jr.; Sobral, 2023), as well as “Destaque Territorial” (“Territorial Highlight”) maps that cross-reference academic production with socioeconomic and environmental vulnerability indices for Brazilian municipalities (Sampaio et al., 2025b). This multidisciplinary trajectory provides a robust framework that informs and enables analysis in the Engineering I area.

Applying these analytical approaches to the specific field of engineering reveals empirical patterns. In a recent study, Ribeiro et al. (2023) used topic modeling to assess the alignment of engineering research at Universidade Federal de Uberlândia (UFU) with the 2030 Agenda and demonstrated a marked concentration of studies focused on SDG 9, which alone accounted for 55% of the studies in the analyzed database. SDGs 3, 7, and 12 followed. However, the same study revealed significant gaps: the institutional and social justice dimensions, represented particularly by SDG 16 (Peace, Justice and Strong Institutions) and SDG 17 (Partnerships for the Goals), were not mentioned at all in the re-

sults. This discrepancy corroborates the argument that engineering needs to deepen its understanding of the needs of vulnerable populations and highlights the urgency of investigating, at the national scale, how the Engineering I Evaluation Area is (or is not) integrating dimensions of inclusion and equity into its technological innovations.

This chapter begins precisely from that point. Its objective is to analyze the alignment of Engineering I graduate programs with the SDGs of the 2030 Agenda, based on a nationwide study of master's theses and doctoral dissertations defended between 2021 and 2023. The analysis focuses on understanding the territorial distribution of programs—revealing profound regional asymmetries in production—the temporal evolution of SDG occurrences in academic studies, the relationship between CAPES ratings and the thematic diversity addressed, and, fundamentally, the institutional challenges that remain in achieving a cross-cutting incorporation of the social dimensions needed to ensure sustainable and inclusive technological development.

1.1. Background and thematic rationale

The relevance of the topic derives from two converging and structural movements in the contemporary academic landscape. The first is the growing demand for evidence of the impact of Brazilian graduate education on society, driven by the transition of the National Graduate Education System (SNPG) toward a multidimensional evaluation model. The current CAPES Evaluation Form consolidated the “Impact on Society” criterion, requiring programs to provide evidence of the economic, social, and cultural benefits of their intellectual and technological production (Brasil, 2021b, 2022). The second movement is the undisputed consolidation of the SDGs as an international language of reference for examining contributions to sustainability, innovation, equity, education, and territorial transformation (Findler et al., 2019; Gomes Junior et al., 2023). Higher education institutions have assumed the role of agents of transformation, and the 2030 Agenda offers a logical framework for aligning educational strategies with humanity's major challenges (Ramírez-Mendoza et al., 2020; Ashida, 2023).

In the Engineering I Evaluation Area, this debate takes on particular force because the area occupies a strategic and foundational position in formulating technical solutions to complex public and production-related problems. Construction projects, systems, new materials, sanitation technologies, industrial innovation, production-process efficiency, and responses for adaptation to and mitigation of climate change are cross-cutting themes in the area and are directly connected to the material dimensions of development (Brasil, 2021a). The CAPES Area Document itself (Brasil, 2021a) recognizes that Engineering I

engages with almost all 17 SDGs, while emphasizing a direct and priority connection with SDGs 6, 9, 11, and 13.

Engineering is responsible for designing infrastructure that enables universal access to clean energy sources and sanitation and plays a central role in determining the quality of life of a rapidly growing urban population and the health of the planet as a whole. Moreover, addressing the climate emergency requires engineering solutions that help redesign the entire value chain, decoupling economic growth from its environmental footprint and moving society from linear consumption patterns toward a circular economy (Rahimifard; Trollman, 2018). For technological innovation to fulfill this role, Ramírez-Mendoza et al. (2020) suggest adopting a "Transformative Innovation" model in which engineering education is intentionally directed toward achieving the SDGs by responding to society's real needs through the co-development of solutions.

Even so, measuring this alignment is not simple and reveals disparities. Recent bibliometric and text-mining studies, such as that conducted by Ribeiro et al. (2023) in the engineering programs at UFU, revealed that whereas SDG 9 accounts for 55% of the studies analyzed, there is a complete absence of research focused on SDGs 16 and 17. As Rahimifard and Trollman (2018) caution, the social dimension of the SDGs requires a deep understanding of the specific needs of vulnerable populations and the adoption of a user-centered innovation approach, which engineering still needs to internalize more rigorously.

The postdoctoral project underlying this chapter begins from the observation that there is still no methodological consensus on specific indicators capable of measuring, in a standardized and bias-free manner, the systemic contribution of Engineering I graduate programs to the 2030 Agenda. This measurement gap becomes urgent in light of the system's new evaluation guidelines. The current Engineering I Area Document (Brasil, 2024) defines impact on society fundamentally as the utility and benefits that the products generated by programs bring to the population. The official text makes a central distinction: "products" are the direct results of research, whereas "impacts" are the real and transformative effects that those products cause in the economy or society. Because the document itself emphasizes that mechanisms for transferring knowledge from academia to society are indispensable if impact is actually to occur, counting patents or publications in isolation does not ensure an understanding of this social utility. It is therefore necessary to develop evaluation models based on artificial intelligence and computational linguistics to overcome this methodological barrier (Gomes Junior et al., 2023).

The rationale for this chapter, therefore, is to transform an already completed nationwide study (2021–2023) into an organized and in-depth academic interpretation that can contribute both to scientific discussion in the area and to institutional strategic plan-

ning. By converting the study's results into a structured analytical reading, the text helps demonstrate where the area already makes a consistent and mature contribution, where strong specializations and regional asymmetries exist (a central concern for CAPES in allocating resources and funding), and where thematic gaps merit priority policy action. The study provides essential evidence to help graduate program coordinators align their self-evaluation processes with the social and educational dimensions required to achieve excellence (ratings 6 and 7), promoting an engineering field that serves as a driver of inclusive and sustainable innovation (Brasil, 2024).

Although professional doctorates have been permitted since 2017 (Brasil, 2017)—which would allow professional programs to attain ratings 6 and 7—the Engineering I Evaluation Area has only one professional doctorate. This doctoral course was recommended at the end of 2025 and is currently listed with the status “em projeto.” Under CAPES guidelines, a doctoral course must have operated actively throughout the two most recent complete four-year evaluation cycles for a program to be eligible for a recommendation of excellence (ratings 6 and 7) (Brasil, 2025).

2. ENGINEERING I AND THE 2030 AGENDA

The relationship between Engineering I and the 2030 Agenda goes beyond the merely rhetorical use or cosmetic adoption of the language of the SDGs in institutional reports. It is manifested primarily in the area's vocation and historical capacity to produce applied knowledge aimed at addressing concrete and material challenges facing society. This perspective is consistent with the understanding that engineering education and research should connect technological innovation with social development, expanding their contribution to complex public problems (Marjoram, 2015). This ranges from research on resilient infrastructure and technological innovation to in-depth studies addressing climate mitigation, water management, industrial process efficiency, production sustainability, and, ultimately, improved living conditions (Rahimifard; Trollman, 2018; Ramírez-Mendoza et al., 2020). According to the CAPES Area Document, activities carried out within Engineering I are closely linked to the 2030 Agenda as a whole, with particular emphasis on an organic and direct connection with SDGs 6, 9, 11, and 13 (Brasil, 2024).

Accordingly, the area tends to connect more strongly with SDGs related to technological and environmental domains. Engineering plays a central role in determining the quality of life of a rapidly growing urban population and is a driving force for enabling universal access to clean energy sources, basic sanitation, and low-carbon mobility (Rahimifard;

Trollman, 2018). To address these structural challenges, new pedagogical and research approaches grounded in Transformative Innovation and the transition to Industry 4.0 have been incorporated. These approaches encourage the area to rethink the design of industrial processes, pursuing process intensification through the lenses of the circular economy, a sharp reduction in greenhouse gas emissions, and greater efficiency in the use of materials and energy (Ramírez-Mendoza et al., 2020). Such advances are fundamental to meeting the need for highly qualified human resources required by Brazil's current neo-industrialization and energy-transition policy (Brasil, 2025).

However, the nationwide study analyzed in this chapter shows that this connection is not homogeneous. Some SDGs are widely prioritized—reflecting engineering's tradition and research "core"—whereas others appear only as secondary themes, and some remain notably underrepresented. There is a lack of cross-cutting integration, particularly for goals related to equity, governance, and social dimensions that are less traditional in the exact sciences, such as SDG 5 (Gender Equality), SDG 10 (Reduced Inequalities), and SDG 16. A bibliometric study focused on topic modeling corroborates this tendency: in assessing the alignment of engineering research at UFU, it revealed that, although there is a very high concentration of studies on infrastructure and innovation (SDG 9), references to institutional justice, inclusion, and global partnerships (SDGs 16 and 17) are almost entirely absent (Ribeiro et al., 2023).

This gap reflects a critical divide that must be overcome. For innovation to achieve its full transformative potential, the social and societal dimensions of the SDGs require engineering to develop a deep understanding of the needs of users in vulnerable situations and to adopt a human-centered approach (Rahimifard; Trollman, 2018). Solving complex, or wicked, problems requires more than technical competence; it calls for the development of key sustainability competencies, such as systems-thinking competence, anticipatory competence, and normative competence, enabling researchers to evaluate the socioenvironmental trade-offs of technological interventions even before implementing them (Wiek; Withycombe; Redman, 2011).

This observation prevents two simplifications in science policy. The first would be to assert that the area already operates in a fully cross-cutting and holistic manner across the entire 2030 Agenda, which would obscure methodological shortcomings in addressing social justice, governance, and inclusion. The second would be to disregard the real and structural strength of existing contributions, which have ensured vital advances in infrastructure resilience, disaster management, and the development of innovations with substantial economic and environmental impact. The data indicate an area with a strong and consolidated presence in certain strategic domains focused on the built environment and production systems, but with considerable room—and an institutional obligation es-

tablished by the new CAPES evaluation criteria—to expand its thematic integration. The future of Engineering I graduate education requires diversification of impacts, promoting solutions that combine the frontier of technological knowledge with social engagement to address problems in Brazilian society and actively contribute to reducing regional asymmetries (Brasil, 2025).

3. METHODOLOGICAL APPROACH

This chapter adopts an exploratory and descriptive analytical-interpretive approach grounded in the extraction and systematization of secondary data from an extensive nationwide study of the alignment of the Engineering I Evaluation Area with the SDGs. The empirical basis of this research comprises 5,878 academic studies (master's theses and doctoral dissertations) defended and published between 2021 and 2023. This analytical corpus was constructed by collecting data from official repositories: the CAPES Open Data portal was used for 2021 and 2022, and web scraping was performed directly on the Sucupira Platform for 2023. All extracted records were consolidated, standardized, and organized in a data matrix containing the year of defense, the name of the graduate program, the title of the study, the abstract, the keywords, and the program's rating within the SNPG.

The systematic identification of research alignment with the SDGs was carried out with the support of the ImpactoSociedade software (developed in association with the work of the Núcleo de Pesquisa em Impacto da Pós-Graduação na Sociedade – NuPIS: www.nupis.com.br), an advanced computational artifact that uses combined text mining and natural language processing (NLP) techniques to examine the semantic content of textual materials (Gomes Junior et al., 2023). Relying solely on isolated keyword searches or manual classification for a volume of nearly six thousand documents would make the process impracticable and susceptible to cognitive bias. The algorithm therefore enables the identification of patterns, the extraction of meaningful associations, and the automated and standardized modeling of knowledge in large volumes of unstructured data (Sampaio et al., 2020; Gomes Junior et al., 2023).

The computational model's algorithmic procedure is structured in sequential and interdependent stages (Gomes Junior, 2019). First, the algorithm cleans the text, acting as a lexical analyzer that removes special characters, numbers, punctuation, and stopwords (words without semantic relevance, such as prepositions and articles), thereby standardizing the texts. An n-ary structure (n-ary tree) is then assembled, in which the captured

words are added to a data structure and subjected to stemming (reducing words to their stems or removing suffixes), generating clean graphs (Sampaio et al., 2020).

The third stage consists of constructing a complex co-occurrence network (graph construction), which maps the adjacency of words in the text. At this stage, statistical weights are applied, including TF-IDF (term frequency–inverse document frequency), a metric that assesses the relevance of a word in a document relative to the entire corpus, together with the calculation of term entropy to define semantic weights at the network nodes (Gomes Junior et al., 2023).

Next, n-grams (contiguous sequences of words) are captured and a Markov matrix is formulated; its stochastic model makes it possible to calculate the probabilities of occurrence and transition among word sequences in the text.

Finally, feature vectors are extracted in structural, statistical, and spectral dimensions. Based on this vectorization process, the software performs a semantic comparison by calculating the edit distance between the tree generated from the corpus under evaluation (the engineering abstracts and titles) and the reference corpus (the official descriptors of the 17 SDGs, previously translated, calibrated, and validated by specialists). As a result, the algorithm is able to associate master's theses and doctoral dissertations with the SDGs with a high degree of accuracy, producing cross-tabulated analyses by state, region, CAPES rating, and thematic frequency (Sampaio et al., 2020; Gomes Junior et al., 2023).

The empirical basis and analytical procedure are summarized in Table 1.

Table 1 – Summary of the empirical basis and analytical procedure

Element	Summary
Period	2021–2023
Database	CAPES Open Data portal (2021–2022) and Sucupira Platform, using web scraping (2023)
Empirical unit	5,878 academic studies organized by year, program, title, abstract, and rating
Analytical tool	ImpactoSociedade software with text mining
Main stages	Text cleaning, n-ary tree, co-occurrence network, Markov matrix, and feature-vector extraction
Analytical outputs	Analyses by state, region, SDG frequency, CAPES rating, and mean SDGs/study

3.1. Summary of the analytical procedure

The methodological workflow can be summarized in four interconnected stages: collection of the CAPES/Sucupira database; textual processing of the records; automated identification of alignment with the SDGs using ImpactoSociedade; and consolidation of analyses by territory, time, rating, and thematic frequency. Figure 1 summarizes this process.

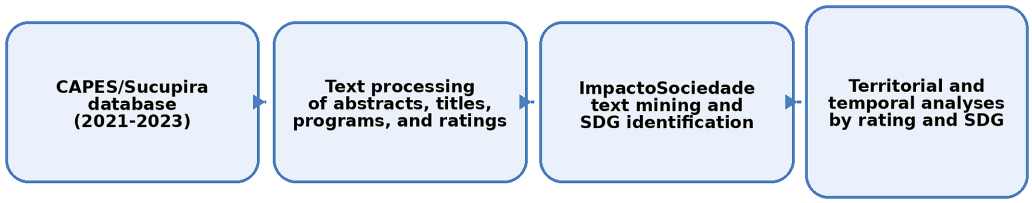


Figure 1 – Summary flow of the analytical procedure adopted in the Engineering I study.

3.2. Scope

This text does not claim to settle the methodological debate on measuring alignment with the 2030 Agenda, nor does it seek to resolve definitively whether academic abstracts are the best or only possible basis for this type of algorithmic classification. The CAPES system itself recognizes that measuring complex impacts requires continuous improvement (Brasil, 2021a). What is presented here is a consistent interpretive perspective, enabled by a computational tool and supported by a large-scale study, capable of revealing relevant national patterns and assisting area coordinators and public policymakers in the transition toward engineering that is more oriented to ecosocioeconomic development.

4. RESULTS AND DISCUSSION

The results are presented and discussed according to four analytical dimensions:

4.1 Territorial distribution of programs and regional asymmetries: maps the concentration and dispersion of Engineering I graduate programs across Brazil, highlighting historical asymmetries between the South-Southeast axis and the country's other regions;

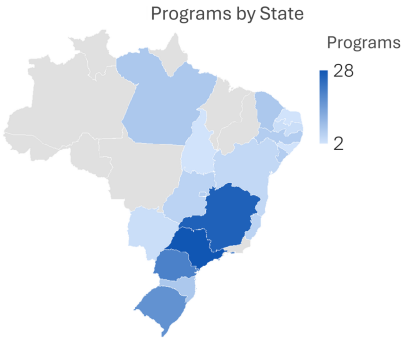
4.2 Thematic concentration and core areas of activity: identifies the most recurrent SDGs in the area, emphasizing Engineering I's predominant thematic clusters, including climate, infrastructure, sanitation, innovation, and water;

4.3 Program evaluation and mean SDG diversity: cross-references the programs' CAPES ratings with the mean density of SDGs per study, making it possible to identify differences between absolute production volume and relative thematic diversity;

4.4 Gaps and challenges in expanding alignment: discusses underrepresented SDGs, particularly those associated with the social, institutional, cultural, and territorial dimensions of sustainable development.

4.1. Territorial distribution of programs and regional asymmetries

The geographic distribution of Engineering I graduate programs reveals a strong concentration in Brazil's Southeast and South regions. The state of São Paulo leads nationally with 28 programs, followed by Minas Gerais with 26 and Paraná with 20. At the other end of the spectrum, the North region has a much more limited presence, with programs identified in only a few states. This picture is reinforced by the complete absence of Engineering I graduate programs in states such as Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Piauí, Rondônia, and Roraima, as illustrated in Figure 2.



State	Programs
São Paulo	28
Minas Gerais	26
Paraná	20
Rio de Janeiro	20
Rio Grande do Sul	17
Ceará	7
Pará	7
Santa Catarina	7
Distrito Federal	6
Pernambuco	6

State	Programs
Sergipe	6
Espírito Santo	5
Goiás	5
Bahia	4
Mato Grosso do Sul	3
Paraíba	3
Alagoas	2
Rio Grande do Norte	2
Tocantins	2

Figure 2 – Geographic distribution of Engineering I graduate programs by state.

This pattern is relevant to science policy for two structural reasons. First, it confirms the persistence of profound historical asymmetries in the distribution of Brazilian graduate education. Second, this concentration tends to influence not only the absolute vol-

ume of academic and technological production but also the geography of contributions to the SDGs and the resolution of local problems. In other words, states with a higher density of programs (and greater installed capacity) tend to have an overwhelming absolute weight in occurrences of alignment, although this does not necessarily indicate greater mean SDG diversity per individual study. Nevertheless, a shift toward decentralization is apparent: relative growth in SDG occurrences in studies from the North, Northeast, and Central-West regions reached +37.8% during the period, a faster expansion than in the Southeast (+16.0%) and South (+12.5%), as shown in Figure 3.

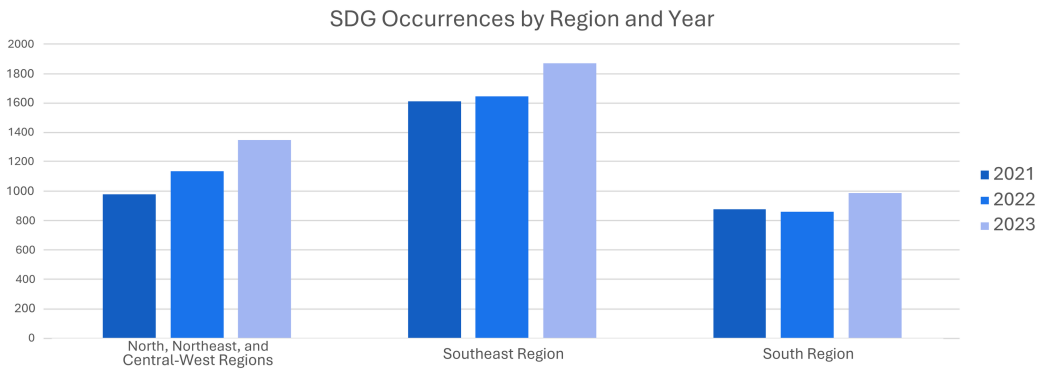


Figure 3 – Evolution of SDG occurrences by Brazilian region in Engineering I (2021–2023).

4.2. Thematic concentration and core areas of activity

The analysis reveals that Engineering I has a thematic core strongly oriented toward technical sustainability, infrastructure, and climate response, as illustrated in Figure 4.

This profile is highly consistent with the nature and educational scope of the area, but it also reveals a strong concentration on goals that are closer to the traditional engineering repertoire. The CAPES Area Document had already indicated this historical vocation, noting that Engineering I activities have a direct and priority connection with SDGs 6, 9, 11, and 13. Figure 5 shows how the five most recurrent SDGs are distributed across the territory.

The quantitative study confirmed this pattern of thematic concentration. Only five SDGs accounted for 6,881 occurrences out of a total of 11,111 semantic associations extracted from texts across the area. SDG 13 occupies a central position in the agenda as the most frequent goal, with 2,235 occurrences. Specific bibliometric research corroborates

this pattern in institutional samples. Using topic modeling in engineering courses at UFU, Ribeiro et al. (2023) found that 55% of the academic studies in the database were primarily aligned with SDG 9, followed by SDGs 3, 7, 12, and 6. Table 2 systematizes the main quantitative findings for this dimension at the national scale.

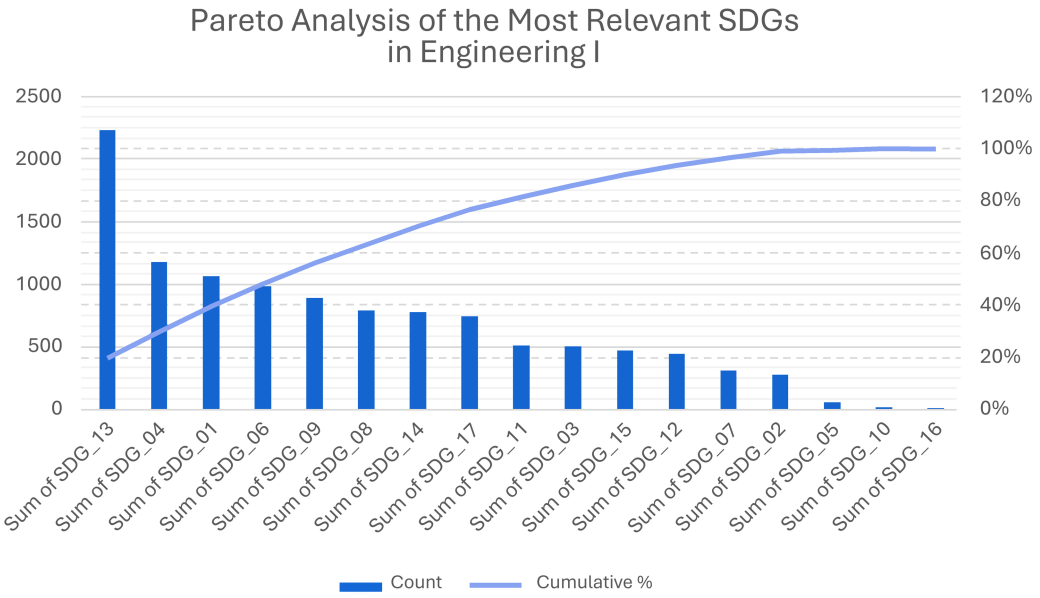


Figure 4 – Concentration of SDG occurrences in Engineering I: share of the five most frequent SDGs in total occurrences.

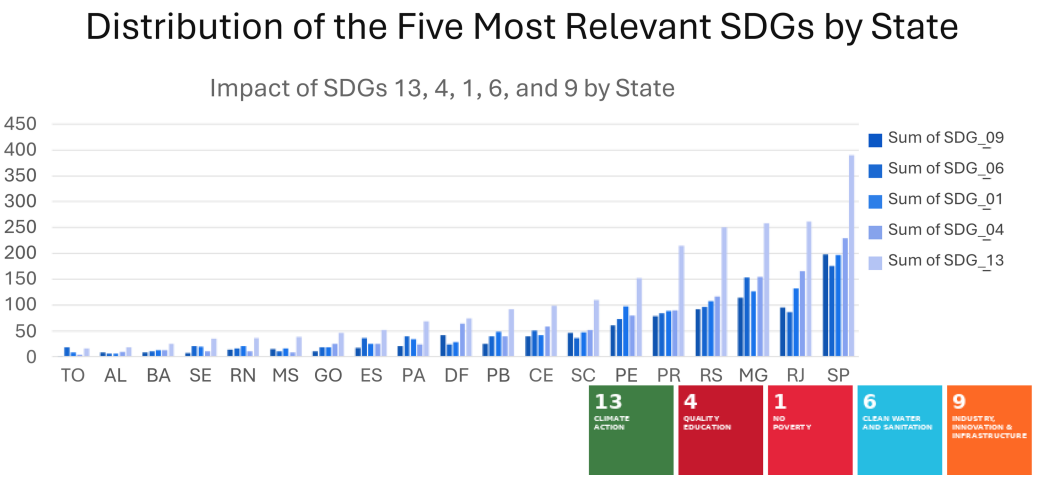


Figure 5 – Territorial distribution of the five most recurrent SDGs in Engineering I graduate programs.

Table 2 – Main quantitative findings of the study

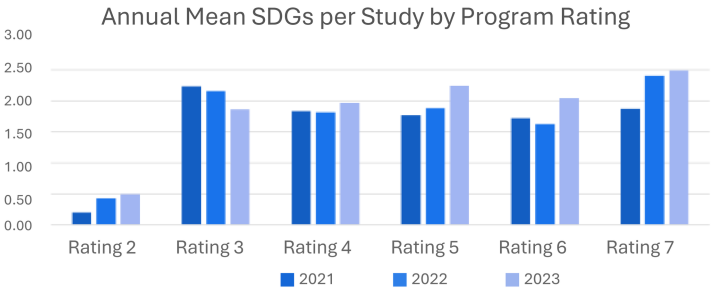
Dimension	Finding	Interpretation
Distribution of programs	SP 28; MG 26; PR 20	Structural concentration in the Southeast and South
Occurrences by state	SP 2,111; MG 1,457; RJ 1,279	Absolute numbers of alignment with the SDGs in Brazil are higher in states with a stronger academic tradition and more extensive academic infrastructure
Studies by state	SP 1,009; MG 736; RJ 721	Predominance of the area's main historical hubs
Regional growth in SDGs	N/NE/CW +37.8%; Southeast +16.0%; South +12.5%	Faster relative expansion outside the traditional axis
Most frequent SDG	SDG 13 with 2,235 occurrences	Centrality of the climate agenda
Thematic concentration	5 SDGs account for 6,881 of 11,111 occurrences	Predominance of a few goals in the area's total
Evaluation and volume	Rating 4 accounts for 1,863 studies	Intermediate programs sustain a large share of production
Mean SDGs/study	Rating 7 = 2.22; rating 3 = 2.02	Volume and thematic diversity do not always move together

4.3. Program evaluation and mean SDG diversity

Cross-referencing data on alignment with the SDGs and the ratings assigned within the SNPG reveals dynamics relevant to strategic planning in Engineering I. In quantitative terms, programs rated 3 and 4 play a decisive role in the total volume of identified contributions. Programs rated 4 alone account for 1,863 studies in the period examined, making this the stratum with the highest absolute number of master's theses and doctoral dissertations associated with the SDGs. In raw occurrences, strata 3 and 4 lead in alignment with nearly all global goals, whereas programs rated 2 have only a residual presence, with just 8 occurrences recorded in the study. This pattern indicates that the base of programs undergoing consolidation sustains a substantial share of academic production aligned with the 2030 Agenda.

When the analytical focus shifts from absolute volume to the mean number of SDGs per study, however, more complex patterns emerge. Rating 7 leads, with a mean of 2.22 SDGs per study. Rating 3, in turn, has an overall mean of 2.02 SDGs per study, placing it above ratings 4, 5, and 6 for the three-year period as a whole, although ratings 4, 5, and

6 exceeded rating 3 in the specific 2023 results. Figure 6 summarizes this relationship between program evaluation and mean SDG diversity per study.



CAPES Rating	Overall Mean (2021-2023)
7	2.22
3	2.02
5	1.94
4	1.88
6	1.74
2	0.40

Figure 6 – Annual mean number of SDGs per study by CAPES rating of Engineering I graduate programs.

This result is relevant because it demonstrates that absolute production volume and relative thematic diversity are not equivalent dimensions. Programs in the intermediate strata, particularly those rated 4 and 5, tend to account for a large volume of studies, but that volume may be associated with greater thematic specialization, with research vertically focused on specific technological niches. Programs rated 7, by contrast, tend, by virtue of their excellence status, to mobilize more complex and transdisciplinary approaches that connect technological innovation, climate resilience, sustainable infrastructure, and socioeconomic impact.

For programs rated 3, the high mean number of SDGs per study may be related to their strategic role in territorial contexts marked by regional asymmetries. Programs undergoing consolidation, often located outside the main research centers, tend to respond to multifaceted local demands that connect technology, water resources, sanitation, poverty, infrastructure, and territorial development. Their production may therefore display greater thematic dispersion, not necessarily because of greater scientific maturity, but because of the need to address complex and interdependent local problems.

From an institutional perspective, this finding shifts the discussion from a merely productivist reading toward a qualitative analysis of alignment with the SDGs. It is not sufficient to observe how many studies were produced; it is necessary to examine how many goals are mobilized, at what density, and in what thematic combinations. The relationship between CAPES rating and SDG diversity may therefore inform targeted policy measures, cooperation networks, interinstitutional solidarity strategies, and the strengthening of peripheral programs, particularly when linked to the agenda of social impact and sustainable development.

4.4. Gaps and challenges in expanding alignment

On the one hand, the study highlights the strength of Engineering I in climate response, infrastructure, innovation, and sanitation; on the other, it also reveals thematic gaps that the area still needs to address. SDGs concerned with social and institutional dimensions, such as SDGs 5, 10, and 16, have low representation among the master's theses and doctoral dissertations analyzed. Other themes relevant to a broader reading of sustainable development, such as health and well-being associated with the built environment, urban inclusion, territorial governance, and socioenvironmental justice, also remain underexplored.

This pattern does not mean that innovations promoted by Engineering I graduate programs are disconnected from social impacts. Rather, it means that these dimensions appear less explicitly in study designs, in the formulation of abstracts, and in the academic language used to describe research results. The low occurrence of social SDGs may therefore reflect both a real thematic gap and a limitation in explicitly articulating existing social impacts.

Recent literature reinforces this concern. In analyzing engineering research through topic-modeling techniques, Ribeiro et al. (2023) identified a strong concentration on SDG 9, whereas goals associated with justice, strong institutions, and global partnerships had a residual or nonexistent presence. This result suggests that engineering still needs to make progress in explicitly incorporating the social, cultural, and institutional dimensions of the SDGs, particularly when its interventions directly affect territories, vulnerable populations, and living conditions.

In practical terms, this points to a scientific and institutional agenda for strengthening interdisciplinary research, expanding dialogue with communities affected by infrastructure and technologies, and integrating the design of technical solutions more clearly with their effects on inclusion, governance, equity, and quality of life. This perspective converges with Compan et al. (2024), who emphasize the importance of sustainability indicators capable of measuring the social impact of university-community engagement programs. This expansion is particularly important in light of new CAPES evaluation guidelines, which tend to require programs to demonstrate more fully their social impact, equity policies, technological accessibility, and concrete contribution to historically vulnerable populations and territories.

The discussion also broadens when Brazil's internalization of the 2030 Agenda is considered, including the proposal of complementary SDGs such as SDG 18 (Ethnic-Racial Equality), SDG 19 (Art, Culture and Communication), and SDG 20 (Rights of Indigenous Peoples and Traditional Communities). This expansion is particularly relevant to

Engineering I because major construction projects, sanitation systems, urban infrastructure, highways, dams, and territorial interventions frequently cross or affect traditional communities, peripheral areas, and populations in vulnerable situations. Incorporating these dimensions does not mean altering the character of the area, but rather enhancing its ability to demonstrate sustainable, inclusive, and territorially responsible impact.

Finally, a methodological agenda remains open. Analysis based on abstracts and keywords allows scale, comparability, and reproducibility, but it may not capture all the cross-cutting dimensions present in the full texts of master's theses and doctoral dissertations. It is also necessary to deepen the conceptual definition of “alignment” with the SDGs, distinguishing the mere presence of terms associated with the goals from an actual intention to generate social, environmental, economic, or institutional impact. These limitations do not invalidate the results presented; on the contrary, they indicate that the field of measuring the impact of graduate education on the 2030 Agenda is still being consolidated and continues to offer considerable scope for analytical, computational, and interpretive refinement.

5. FINAL CONSIDERATIONS

This chapter has shown that Engineering I graduate programs make an effective and structural contribution to achieving the 2030 Agenda. However, this contribution is substantially concentrated in certain thematic cores and strongly clustered in specific territories of the country. SDG 13 is the most frequent, followed by SDG 9; SDGs 6 and 11 appear as regional specializations. Taken together, these findings indicate an area connected to technical sustainability, infrastructure provision, process innovation, and responses to environmental challenges (Rahimifard; Trollman, 2018; Brasil, 2022). This alignment profile is highly consistent with engineering's vocational identity and its role in designing solutions for mitigating physical impacts and adapting to climate change.

At the same time, the empirical results make clear that the area can—and must—advance toward a more systematic and cross-cutting incorporation of the social and institutional dimensions advocated by sustainable development. The low representation of SDGs related to equity, governance, and social justice (SDGs 5, 10, and 16) suggests a latent opportunity to broaden and deepen the research agenda. The reference study conducted by Ribeiro et al. (2023), which analyzed engineering research databases using artificial intelligence, supports this concern by showing that goals related to peace, justice, and strong institutions (SDG 16), as well as the promotion of global partnerships (SDG 17), are not even mentioned or categorized in the algorithmic models.

The central point is not to displace Engineering I from its own methodological field or exact-sciences foundation, but to expand its analytical capacity to articulate broader impacts by demonstrating how its innovations and technical-technological products (PTTs) directly affect the reduction of vulnerabilities and the promotion of quality of life (Findler et al., 2019).

From the perspective of science policy and the strategic management of graduate education, the interpretation produced by this study (2021–2023) offers three contributions to the area.

The first is to make the existing contribution of Engineering I graduate programs to the 2030 Agenda visible in a standardized manner and at the national scale. With the consolidation of the "Impact on Society" dimension in the CAPES Evaluation Form, translating the production of master's theses and doctoral dissertations into the universal language of the SDGs enables the area to demonstrate its value to society and justify the public funding it receives by showing that its research resolves Brazil's production and environmental bottlenecks.

The second contribution is to identify and map the profound territorial inequalities that must be considered in targeted incentive policies and institutional strengthening strategies. The concentration of master's theses and doctoral dissertations and of SDG occurrences in the Southeast and South reflects the historical asymmetry in the installed capacity of the SNPG. Thus, SDG mapping serves as an instrument for CAPES policies to direct resources, interinstitutional solidarity calls for proposals (such as those for Interinstitutional Master's and Doctoral Programs – Minter and Dinter), and priority funding toward the North, Northeast, and Central-West regions, ensuring that technological development reaches the biomes and populations that most need sustainable infrastructure and sanitation.

The third contribution is to demonstrate that alignment with the SDGs, when measured using robust text-mining and semantic-modeling methodologies, should be treated as an instrument for the strategic analysis of academic production (Gomes Junior et al., 2023). This tool supports area and program coordinators in making decisions on funding priorities, identifying thematic gaps in curricula, encouraging networked cooperation (such as the formation of thematic clusters), and positioning graduate programs to attain ratings of international excellence (ratings 6 and 7).

In summary, the nationwide study for the 2021–2023 three-year period supports the conclusion that Engineering I already participates actively and structurally in the 2030 Agenda, sustaining the domains of climate resilience, infrastructure innovation, and sanitation management. Particularly noteworthy is that the Engineering I Area Document for the 2025–2028 four-year evaluation cycle already places substantial policy emphasis

on alignment with the UN 2030 Agenda, while also incorporating Brazil's proposed complementary SDGs (SDGs 18, 19, and 20), currently under discussion within the National Commission for the Sustainable Development Goals (CNODS).

The next methodological and institutional step is to deepen this analysis by specific areas of concentration and lines of research; improve and refine the algorithmic criteria for what is defined as "alignment"; and, crucially, strengthen the connection between the design of technical production and its direct effects on social justice and territorial transformation. It is through this transition toward complex and interdisciplinary sustainability science that Engineering I will be able to consolidate its principal contribution: not merely acting as an isolated producer of technological innovations and patents, but establishing itself as an active, inseparable, and leading part of a more comprehensive and sustainable development project for the Brazilian state and society.

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Authors

Ailton José dos Santos
Master's student in Civil Engineering at Universidade São Judas Tadeu (USJT), researching the application of artificial intelligence to construction systems aimed at sustainability. Civil engineer, control and automation engineer, and holder of bachelor's degrees in Data Science and Information Technology, with an Executive MBA in Project Management and specializations in Artificial Intelligence, Power Systems and Automation, Architecture and Urban Design, and Occupational Safety Engineering. Engineering and Technology instructor at SENAI-SP, with experience in autonomous robotics, industrial automation, photovoltaic system sizing, and machine safety. Also works as a generative AI engineer, with AI agents, retrieval-augmented generation (RAG), computer vision, and governance, and develops digital twins and BIM modeling for infrastructure simulation and optimization.

Albert de la Fuente Antequera
Ph.D., M.Sc., and degree in Civil Engineering from the Universitat Politècnica de Catalunya (UPC). Associate Professor in the Department of Civil and Environmental Engineering at UPC.

Alessandra Spinelli Sant'Anna
Affiliated with the Graduate Program in Civil Engineering at Universidade São Judas Tadeu (USJT); building technician from ETEC Getúlio Vargas (2014). Has experience in Civil Engineering, with an emphasis on structures.

Alicia Martinez Batista
M.Sc. in Civil Engineering and civil engineer from Universidade São Judas Tadeu (USJT).

Ana Paula Branco do Nascimento
Ph.D. in Applied Ecology from the "Luiz de Queiroz" College of Agriculture of the University of São Paulo (ESALQ-USP) and biologist. Faculty member of the Professional Master's Program in Civil Engineering and of the Department of Health at Universidade São Judas Tadeu (USJT), and research scientist at Instituto Ânima. Carries out teaching, research, and outreach on health and sustainability from an interdisciplinary perspective, connecting these areas to the targets of the 2030 Agenda. Member of the Municipal SDG Commission of São Paulo.

António José Guerner Dias

Ph.D. in Geosciences and degree in Geology from the University of Porto. Assistant Professor in the Department of Geosciences, Environment and Spatial Planning of the Faculty of Sciences of the University of Porto. Works in teaching, research, and outreach in Geosciences, Environment, and Sustainability, with a focus on the relationship between society, natural resources, and the environment, including studies on climate change, natural resource management, solid waste management, and environmental impact assessment.

Arlindo Philippi Junior

Habilitation (*Livre-docência*) in Environmental Policy and Management from the University of São Paulo (USP), postdoctoral studies in Urban and Regional Studies at MIT (USA), and Ph.D. and M.Sc. in Public and Environmental Health from USP. Full Professor at USP, he is Chief of Staff to the Rector and coordinator of the Climate and Sustainability Chair at the Institute of Advanced Studies. At USP, he served as head of the Department of Environmental Health, chair of the Graduate Committee of the School of Public Health, mayor of the USP campus in the capital, and deputy provost for Graduate Studies. At CAPES, he was a member of the Higher Council, coordinator of the Interdisciplinary and Environmental Sciences areas, and Director of Evaluation.

Carlos Alberto Cioce Sampaio

Ph.D. and M.Sc. in Organizational Planning and Management for Sustainable Development from the Federal University of Santa Catarina (UFSC), with a sandwich period in Social Economy at the École des Hautes Études en Sciences Sociales (EHESS, France), and degree in Business Administration from the Pontifical Catholic University of São Paulo (PUCSP). Permanent faculty member of the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu (USJT) and, as a retired volunteer, of the Master's and Doctoral Program in Regional Development at the Regional University of Blumenau (FURB). Research Productivity Fellow of the National Council for Scientific and Technological Development (CNPq) and coordinator of the Environmental Sciences Area at CAPES (2026-2030). He has been a visiting professor in Chile, Spain, and the United States (Fulbright fellowship). Coordinates the Ecosocioeconomics Research Group and is a senior researcher at the Research Group on the Impact of Graduate Education on Society (NuPIS). A pioneer in research on the Ecosocioeconomics of Organizations, with an emphasis on ESG, sustainable territorial development, and community-based tourism in Latin America.

Carlos Herrera Mesén

Professional at Hormiconsa, in Barcelona (Spain).

Cláudia Terezinha Kniess

Postdoctoral studies in Nuclear Technology at the Nuclear and Energy Research Institute (IPEN-CCN/USP), Ph.D. in Materials Science and Engineering, with a sandwich period at the University of Aveiro (Portugal), and M.Sc. in Chemical Engineering from the Federal University of Santa Catarina (UFSC). Bachelor's degrees in Chemistry from UFSC and in Business Administration from the University of Southern Santa Catarina (UNISUL). Associate Professor at the Federal University of São Paulo (UNIFESP), in the Graduate Program in Digital Transformation and Sustainability in Organizations and Society; faculty member and researcher of the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu (USJT) and of the Graduate Program in Business Administration at UNISUL. Coordinates the Research Group on the Impact of Graduate Education on Society (NuPIS) and the Laboratory for the Promotion of University Outreach (LABEX-UNIFESP).

Cleber de Souza Amaral

Master's student in the Graduate Program in Civil Engineering at Universidade São Judas Tadeu (USJT) and civil engineer. Researcher at PROLAB Engenharia de Construção, working on research, development, and innovation projects in materials technology and shrinkage control in industrial floors. His work contributes to integrating applied research and innovative solutions for the construction industry.

Daniela Aparecida de Dutra Lima

M.Sc. in Civil Engineering and civil engineer from Universidade São Judas Tadeu (USJT). Researcher at PROLAB Engenharia de Construção, conducting research on sustainability in construction, with an emphasis on the use of construction and demolition waste, sustainable mortars, and fiber-reinforced concrete.

Denis Becker

Graduate student in the Graduate Program in Civil Engineering at Universidade São Judas Tadeu (USJT).

Dimas Alan Strauss Rambo

Postdoctoral studies at the Polytechnic School of the University of São Paulo (USP), Ph.D. and M.Sc. in Civil Engineering from the Federal University of Rio de Janeiro (UFRJ), and civil engineer from the Regional University of Northwestern Rio Grande do Sul (UNIJUÍ). Undergraduate and graduate professor at Universidade São Judas Tadeu (USJT) and researcher at Instituto Ânima, working on cementitious materials, cementitious composites, and fiber-reinforced concrete for tunnels and industrial floors. Research Productivity Fellow of the National Council for Scientific and Technological Development (CNPq) and partner-owner of PROLAB Engenharia de Construção. Recipient of the Best Doctoral Thesis in Civil Engineering Award in the state of Rio de Janeiro, granted by the Association of Engineering Companies of Rio de Janeiro (AEERJ).

Doris Jimena Roncancio Benítez

Ph.D. and M.Sc. in Public Health from the University of São Paulo (USP) and environmental engineer. Coordinator of the Master's Program in Environmental Health at the Faculty of Engineering of Universidad El Bosque (Colombia) and member of the Water, Health and Environment research group. Her work focuses on the interface between health, climate change, and disaster risk management, with an emphasis on environmental justice and territorial sustainability, contributing to the formulation of adaptation strategies and evidence-based public policies. She also works in academic leadership, curriculum development, and professional training, and in applied research on environmental determinants of health in Latin American contexts.

Enio Ricardo Dorvil Coelho

Specialist in Engineering from the Federal University of Rio Grande do Sul (UFRGS) and civil engineer from the Federal University of Santa Maria (UFSM). He taught at Universidade do Vale do Rio dos Sinos (UNISINOS) from 2008 to 2013, in Surveying I and II, Introduction to Engineering, Structural Analysis, Building Construction, and Architecture Seminars. Has experience in Civil Engineering, with an emphasis on steel structures and reinforced concrete.

Felipe Augusto da Silva Barbosa

Ph.D. and M.Sc. in Civil Engineering from the University of São Paulo (USP) and civil engineer from the Federal University of Paraíba (UFPB). Adjunct Professor at the Federal Rural University of Pernambuco (UFRPE).

Felipe Augusto Matiello Bissoli

Master's student in Civil Engineering at Universidade São Judas Tadeu (USJT), specialist in Concrete Building Structural Systems from Faculdade UNIRIOS, civil engineer from the University of Sorocaba (UNISO), and graduate in Social Sciences from the State University of Londrina (UEL), with technical training in Building from ETEC de Sorocaba. Works in structural design, coordination of technical disciplines, BIM modeling, and civil project management, focusing on construction efficiency, reduction of rework, and digital integration of structures and building services. His research interests include innovation in construction systems, digital processes, and sustainability in construction.

Fernando Gabriel Benitez Jara

Ph.D. and M.Sc. from the Graduate Program in Nuclear Technology – Materials at the Nuclear and Energy Research Institute of the University of São Paulo (IPEN-USP), with a doctoral sandwich period at the Niels Bohr Institute of the University of Copenhagen (Denmark), and degree in Physics from the Facultad de Ciencias Exactas y Naturales of the Universidad Nacional de Asunción (FACEN-UNA, Paraguay). Postdoctoral researcher at IPEN-USP, in collaboration with the Niels Bohr Institute, investigating advanced materials for energy storage, with a focus on electrochemical double-layer supercapacitors. His research combines neutron and X-ray spectroscopy, mathematical modeling, and computer simulation (molecular dynamics).

Francinaldo Alves da Silva

M.Sc. in Civil Engineering from Universidade São Judas Tadeu (USJT), specialist in Occupational Safety Engineering (*lato sensu*), and civil engineer from the University of Mogi das Cruzes (UMC). Has worked on private-sector developments in the São Paulo Metropolitan Area and as Secretary of Public Works of the municipality of Poá (SP).

Gabriel Miranda Santanna

M.Sc. in Civil Engineering and MBA in Project Management from Universidade São Judas Tadeu (USJT), specialist in Geoprocessing from SENAC, and civil engineer. Leads geoprocessing projects in basic sanitation, using Geographic Information System (GIS) tools to collect, transform, and deliver spatial data. His career includes teaching mathematics and geoprocessing solutions for territorial planning and land use. He also works with applied programming, focusing on Python, BIM, BI, PostGIS, and ArcGIS.

Gabriele Silva Costa de Almeida

Master's student in Civil Engineering at Universidade São Judas Tadeu (USJT) and civil engineer from Universidade Nove de Julho (UNINOVE).

Guilherme da Silva Leme

Graduate student in the Graduate Program in Civil Engineering at Universidade São Judas Tadeu (USJT) and civil engineer from Universidade Presbiteriana Mackenzie. Has experience in Civil Engineering, with an emphasis on building construction.

Guilherme Leite Gaudereto

Ph.D. in Civil Engineering from the University of São Paulo (USP), M.Sc. in Business Administration (professional master's), with an emphasis on Environmental Management and Sustainability, from Universidade Nove de Julho (UNINOVE), and degree in Environmental Management from USP. Professor in the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu (USJT), researcher at Instituto Ânima, and editor-in-chief of the Journal of Urban Technology and Sustainability. Co-founder of Instituto Trilhas, an organization dedicated to education for sustainability. Works on innovation and sustainability in construction, urban decarbonization, energy transition, and the incorporation of the Sustainable Development Goals (SDGs) into public policies and planning instruments.

Heloisa Candia Hollnagel

Ph.D. and M.Sc. in Sciences from the University of São Paulo (USP), biologist and mathematician. Has worked in higher education since 2001 and is Associate Professor II at the Federal University of São Paulo (UNIFESP), where she is a member of the Graduate Program in Business Administration: Digital Transformation and Sustainability in Organizations and Society. She is also a member of the Professional Master's Program in Civil Engineering (Sustainability) at Universidade São Judas Tadeu (USJT). Her teaching and research cover public policy,

education, entrepreneurship, and organizational sustainability. President of the Pick-upau Environmental Agency and Water Ambassador of the Women for Water Partnership in Brazil.

Ivaldo Silva da Cunha

Master's student in Civil Engineering at Universidade São Judas Tadeu (USJT), specialist in Concrete Structures and Foundations, in Contemporary Philosophy, and in Educational Management, Early Childhood Education and Early Elementary Education. Civil engineer from Faculdade Maurício de Nassau (São Luís), graduate in Philosophy from the Instituto de Estudos Superiores do Maranhão and in Pedagogy from Uniasselvi.

Jorge Luis Gallego Zapata

Ph.D. in Environmental Toxicology, M.Sc. in Urban Engineering, and environmental engineer. Member of the Research Group on Biodiversity, Biotechnology and Bioengineering (GRINBIO) of the Faculty of Engineering of the University of Medellín (Colombia).

José Carmino Gomes Jr.

Ph.D. in Informatics and Knowledge Management and M.Sc. in Business Administration, with an emphasis on Project Management, from Universidade Nove de Julho (UNINOVE), specialist in Mathematical Modeling from the Federal University of ABC (UFABC), and degree in Mathematics (teaching) from UNIABC. Postdoctoral researcher in Regional Development at the Regional University of Blumenau (FURB). Faculty member of the Department of Informatics at Universidade São Judas Tadeu (USJT), in the Computer Science, Systems Analysis and Development, and Information Systems programs, and in the Professional Master's Program in Civil Engineering. Works in software development, natural language processing, graph theory applied to knowledge modeling, and machine learning. Developed the ImpactoSociedade software, designed to analyze the ecosocioeconomic impact of graduate programs, holds seven software registrations at the National Institute of Industrial Property (INPI), and is a member of the Research Group on the Impact of Graduate Education on Society (NuPIS).

Leon Henrique Martins de Mendonça

Master's student at Universidade São Judas Tadeu (USJT), specialist in Geotechnical Engineering, civil engineer, and degree in Mathematics (teaching). Faculty member of the Bachelor's in Civil Engineering at Centro Universitário Fundação Santo André (FSA). His professional career covers basic sanitation works, rail transportation, and building infrastructure. Produces academic work on sustainability, integrating the 2030 Agenda into the challenges for the development of Civil Engineering.

Lucas José Nasraui

Graduate of the Graduate Program in Civil Engineering at Universidade São Judas Tadeu (USJT).

Lucas Maia de Souza
M.Sc. in Civil Engineering and civil engineer from Universidade São Judas Tadeu (USJT). Researcher at PROLAB Engenharia de Construção, he provides civil engineering services to CBJ Serviços de Construção em Geral. Works on construction materials and components, mainly construction and demolition waste, sustainability, characterization and technological control of conventional and fiber-reinforced concrete, and patent information.

Lúcio Carlos de Carvalho Boggian
Ph.D. in Society, Technology and Environment from Universidade Evangélica de Goiás, M.Sc. in Agribusiness from the Federal University of Mato Grosso do Sul (UFMS), and degree in Business Administration from the Pontifical Catholic University of Goiás (PUC Goiás), with an MBA in Digital Media from IPOG and an MBA in Healthcare Management from the Albert Einstein Israelite Institute of Teaching and Research. Postdoctoral researcher in Civil Engineering at Universidade São Judas Tadeu (USJT), studying the impact of Graduate Programs in Civil Engineering on the 2030 Agenda. Product Director at SADI and researcher at the Instituto e Centro de Pesquisa Anexo Brasil, he works on artificial intelligence applied to education and takes part in developing SADI Educação, a pedagogical management support system. Has more than 20 years of executive experience in educational management, including 13 years as administrative director of the Associação Educativa Evangélica, the maintaining institution of Universidade Evangélica de Goiás.

Michele Cavalcanti Toledo
Ph.D. and M.Sc. in Public Health and bachelor's degree in Environmental Management from the University of São Paulo (USP). Works in environmental sciences, human health risk assessment, public health, and environmental education. Has experience in circular economy and waste management, having led private-sector projects with waste generators, recycling cooperatives, and companies across the chain, and served as a UNDP consultant on the inventory of chemical substances under the Stockholm Convention. Member of the Environmental Risk Assessment Research Group (NARA) of the USP School of Public Health and of the Planning and Sustainable Development Research Group of Universidade São Judas Tadeu (USJT). Works in epidemiological surveillance at the São Paulo State Department of Health.

Michele de Jesus Nogueira
M.Sc. in Civil Engineering from Universidade São Judas Tadeu (USJT), postgraduate specialization in Construction Planning and Control, and degrees in Civil Engineering and Business Administration. Founder of Donas da Obra, with 16 years of experience in the field. Construction coordinator for high-end residential buildings and Minha Casa Minha Vida (MCMV) housing projects, with experience in project approvals, construction planning and control, execution, real estate development, and sustainable implementations under AQUA and LEED. Professor in the undergraduate Civil Engineering program at Faculdade Monitor.

Mostafa Galal Abdelfattah Mohamed Aboelkheir

Ph.D. in Polymer Science and Technology from the Federal University of Rio de Janeiro (UFRJ), M.Sc. in Chemistry from UFRJ, in partnership with COPPE/UFRJ, and degree in Chemistry from Ain Shams University (Egypt). Professor in the Professional Master's Program in Civil Engineering and in the undergraduate Civil Engineering program at Universidade São Judas Tadeu (USJT) and researcher at Instituto Ânima SOCIESC de Inovação. Works on sustainable construction materials, cementitious composites, defects and rehabilitation of façades, durability, waste valorization, and digital transformation in construction, including applications of artificial intelligence and machine learning.

Paulo Cesar de Abreu Paiva Junior

Ph.D. candidate and M.Sc. in Social Change and Political Participation from the University of São Paulo (USP), specialist in Project Management – PMI Practices from SENAC, and degree in Public Policy Management from USP. Academic analyst at the Coordination of the Professional Master's and Doctoral Program in Law at FGV Direito SP and consultant to companies, governments, and third-sector organizations. Works in public management, political psychology, social change, and political participation.

Rafael Franklin da Silva Ferreira

M.Sc. in Civil Engineering from Universidade São Judas Tadeu (USJT), specialist in Management and Remediation of Contaminated Sites from SENAC, and environmental engineer. Works in environmental consulting, with projects in contaminated site management, hydrogeology, environmental remediation, and multidisciplinary project management, combining technical knowledge and applied management to address environmental challenges in different sectors of the economy.

Ramoel Serafini

Postdoctoral studies in Civil Engineering at Universidade São Judas Tadeu (USJT), Ph.D. in Civil Engineering from the University of São Paulo (USP), and civil engineer from the University of Caxias do Sul (UCS). Permanent faculty member of the Professional Master's Program in Civil Engineering at USJT. Works on special concretes, fiber-reinforced concrete, structures in fire, and infrastructure works. Received honorable mentions in the CAPES Thesis Award, the USP Outstanding Thesis Award, and the IBRACON Theses and Dissertations Award, all in 2022, and the USJT Teaching Merit Award (2025).

Renan Pícolo Salvador

Postdoctoral studies at the University of São Paulo (USP), Ph.D. from the Universitat Politècnica de Catalunya (UPC, Spain), and M.Sc. and bachelor's degree in Chemistry from USP. Provost for Research at Universidade São Judas Tadeu (USJT), coordinator of the Professional Master's Program in Civil Engineering, and researcher and professor at the institution. Works on cementitious materials, sprayed concrete, fiber-reinforced concrete, and technological in-

novation for the construction industry. He is also partner-owner and technical director of PROLAB Engenharia de Construção.

Roberta Giraldi Romano

Postdoctoral studies in Urban Management, with an emphasis on Public Policy, at the Pontifical Catholic University of Paraná (PUCPR) and in Regional Development, focusing on Ecosocioeconomics, at the Regional University of Blumenau (FURB); Ph.D. and M.Sc. in Environment and Development from the Federal University of Paraná (UFPR); and environmental engineer from PUCPR. Faculty member and researcher of the Professional Graduate Program in Work Management for Quality of the Built Environment at Universidade Santa Úrsula (USU). Former consultant to the Environmental Sciences area at CAPES. Associate editor of the journal Desenvolvimento e Meio Ambiente, she is a member of the research groups Ecosocioeconomics Research Group (NEcos), Research Group on the Impact of Graduate Education on Society (NuPIS), and Governance and Innovation for Sustainable Environments (USU).

Rodrigo Teixeira Bento

Ph.D. in Sciences, in the field of Nuclear Technology – Materials, from the University of São Paulo (USP), M.Sc. in Sciences from USP, and degrees in Mechanical Engineering from Universidade São Judas Tadeu (USJT) and in Industrial Mechatronics from Faculdade Engenheiro Salvador Arena. Adjunct Professor in the Engineering programs and professor in the Professional Master's Program in Civil Engineering at USJT, and researcher at Instituto Ânima de Pesquisa, Inovação e Cultura. Specialist in atomic force microscopy (AFM), X-ray photoelectron spectroscopy (XPS), and Raman spectroscopy, he works in mechanical and materials engineering, with an emphasis on manufacturing processes, nanotechnology, TiO2 films, exfoliated carbon and expanded graphite, heterogeneous photocatalysis, metal-organic chemical vapor deposition (MOCVD), thermochemical treatments, and surface modifications.

Rogério Bazan

Civil engineer from the University of Mogi das Cruzes (UMC), with extensive experience in project management and construction. Project coordinator at Alphapiso Tecnologia em Pisos Industriais, working on industrial floors, foundations, and construction planning, with notable work in technical management and quality control, developing technical solutions for projects of different sizes.

Stefany dos Anjos Coronel

M.Sc. in Civil Engineering and civil engineer from Universidade São Judas Tadeu (USJT).

Thais Reis Silva Rocha

M.Sc. in Civil Engineering from Universidade São Judas Tadeu (USJT), specialist in Higher Education Teaching from Faculdade das Américas (FAM), and civil engineer from FMU, with training in Solid Waste Management and Renewable Energy from the Federal Institute of Brasília (IFB). Her research addresses urban mobility, the management and inspection of re-

silient infrastructure, and the interface between civil engineering, sustainability, and the Sustainable Development Goals (SDGs) of the 2030 Agenda. Works in maintenance engineering for large metro-rail and railway structures.

Victor Agostinho Conceição

M.Sc. in Civil Engineering, with an emphasis on Project Management and BIM, and civil engineer from Universidade São Judas Tadeu (USJT). Civil production manager, working in the management of public and private works, with experience in project design, planning, and execution of large-scale developments, including industrial works, power substations for utilities, transmission lines, and infrastructure projects. Produces academic work on BIM, sustainability, and the 2030 Agenda, integrating management, engineering, and innovation applied to construction.

Wellington Augusto Lopes da Silva

Master's student in the *stricto sensu* Graduate Program in Civil Engineering at Universidade São Judas Tadeu (USJT).

Every construction project begins before work starts on site and ends long after the keys are handed over. It begins with the choice of materials, the energy that will reach people's homes, and the place the city makes for those who will live there. And it carries on in the waste it leaves behind, in the people who work on it, and in the professionals who will train the next generation of engineers.

This book starts from that broad view of civil construction. In eleven chapters, researchers from Brazil and abroad address issues that weigh on the sector today: the energy poverty that persists in a country whose electricity mix is predominantly renewable, urban regeneration and social housing, the uses of artificial intelligence in engineering, the performance of fiber-reinforced concrete, carbon footprint measurement, and the use of industrial and natural waste as raw materials. They also discuss gender inequality on construction sites and in offices, as well as the role of universities and graduate education in the 2030 Agenda.

The book was produced within the Professional Master's Program in Civil Engineering at Universidade São Judas Tadeu and combines academic rigor with practical application. It is useful reading for students, researchers, public managers, and professionals who want to understand how technology, the environment, and society influence one another with every design decision.