1 Challenges and opportunities in construction and demolition waste management for circular economy transition

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1.1 Resource efficiency and the circular economy

Environmental challenges, encompassing biodiversity loss, water pollution, air pollution, soil pollution, resource depletion, and rampant land use, are increasingly imperiling the delicate balance of the Earth's life-support systems (Rockstrom et al., 2009). The global economy currently exhausts over 100,000 million tons of natural resources annually, averaging approximately 13 tons per person. It is imperative to recall the alarming environmental consequences arising from the extraction of these resources, including extensive deforestation, topsoil erosion, air pollution, and water pollution. These impacts further exacerbate the boundaries of biodiversity loss (Pacheco-Torgal & Jalali, 2011; Pacheco-Torgal & Labrincha, 2013). Of this consumption, a staggering 67,000 million tons are converted into atmospheric pollutants, such as carbon dioxide or deposited as solid waste into our oceans each year. Only a fraction, 8400 million tons out of the remaining 35,000 million tons, is effectively reused. With a projected population surge by 2050, demanding a rise in natural resource consumption to 126,000 million tons per year, it is evident that we must bolster resource reuse by an additional 26,000 million tons annually just to mitigate the impact of population growth (Pacheco-Torgal et al., 2021). In this context, the European Union has long ago assumed a leading role into a sustainable future. The Europe 2020 Strategy and its flagship initiative on "A Resource Efficient Europe" (COM, 2011a) set the EU on the path to this transformation. The flagship called for a roadmap "to define medium and long-term objectives and means needed for achieving them". The roadmap to a Resource Efficient Europe (COM, 2011b) proposes a new pathway to action on resource efficiency involving all key stakeholders, sets several milestones for 2030 (recycling 65% of municipal waste; 75% of packaging waste; and reduce landfill to maximum of 10% of municipal waste), and provides a framework explaining how policies interrelate and build on each other in which future actions can be designed and implemented coherently. An important concept, which is a part of the Europe 2020

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Strategy for smart, sustainable, and inclusive growth, is the circular economy (CE) (COM, 2014; EC, 2015). Huysman et al. (2017) cite Preston on the definition of the CE concept as an "open production systems − in which resources are extracted, used to make products and become waste after the product is consumed – should be replaced by systems that reuse and recycle resources and conserve energy". Geissdoerfer et al. (2017) characterize the circular economy as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". Their study conducts a comprehensive conceptual analysis aiming to delineate the similarities and differences between CE and sustainability. Addressing two primary research questions, they not only identify conceptual nuances but also advocate for diversity while emphasizing complementary strategies beneficial for managers and policymakers. Cramer (2017) describe the raw materials transition in the metropolitan area of Amsterdam and highlight the need to advance on the 10 Rs of the circularity ladder as a way to create more value. However, some authors warn about the problems associated with recycling high waste content. In addition, although the concept of CE is already being enforced by several countries, some authors showed that it has several limitations and challenges in light of environmental sustainability. Several authors have described several barriers that could hinder the successful implementation of the CE. Mangla et al. (2017) the most important are identified appropriate methods, tools, techniques, and indicators for cleaner production practices. Ritzén and Sandström (2017) listed the following: "measuring financial benefits of circular economy, financial profitability, missing exchange of information, unclear responsibility distribution, infrastructure/supply chain management, perception of sustainability, risk aversion, product design, and integration into production processes". Korhonen et al. (2018) identified six main challenges such as "concerning thermodynamics, definition of CE system boundaries, and challenges in the governance and management of the CE-type interorganizational and intersectoral material and energy flows". Morseletto (2020) analyzed existing and new CE targets using the 10R framework by Potting et al. (2017). The investigation revealed that most current targets emphasize waste management and resource conservation (R8—Recycle and R9—Recovery). However, these do not fully promote a CE, as recycling and recovery can compromise product integrity. Therefore, R8-—R9 targets should be minimized to support more effective CE strategies (R0—R7). Morseletto proposed new targets for strategies, such as remanufacture, refurbish, repair, reuse, refuse, rethink, and reduce, which are more effective in extending product lifespans and enhancing circularity. Alcalde-Calonge et al. (2022) conducted an extensive literature review and bibliometric analysis of the CE spanning the last 13 years, tracing its development and identifying influential works. Their study revealed a striking surge in scholarly attention toward CE, witnessing a remarkable rise from mere 12 research publications in 2008 to over 2300 in 2020. They also observed a notable shift in the geographical concentration of CE research, transitioning from a predominant focus on China to a growing prominence of Europe on the global stage. Alberich et al. (2023) investigated the implementation of the CE in the EU via public policies, employing a framework to assess diverse future scenarios. Their findings revealed a predominant emphasis on technological solutions and economic growth in current

EU CE policies, potentially insufficient for addressing environmental crises. The authors advocate for a repoliticization of the CE discourse, endorsing alternative, more radical visions that question prevailing economic paradigms and prioritize robust sustainability principles. Embracing the CE concept offers a promising framework for transitioning to regenerative systems, although challenges such as limited recycling capabilities and barriers to implementation remain pertinent. As scholarly attention and policy efforts converge on CE principles, there is a pressing need for holistic approaches that prioritize environmental stewardship alongside economic growth.

1.2 Challenges and innovations in construction and demolition waste management

In 2020, approximately 2.24 billion tons of solid waste were generated globally. Of this, construction and demolition waste (CDW) accounted for at least 30%. Shockingly, an estimated 35% of the world's CDW finds its way into landfills, highlighting a significant challenge in waste management practices (Kabirifar et al., 2020). While Europe has set ambitious targets to address this challenge, their attainment appears to have fallen short. According to the Revised Waste Framework Directive 2008/98/EC (WFD), the minimum recycling percentage for "nonhazardous" CDW in the European Waste Catalog should have reached at least 70% by weight by 2020. However, this would have required a consistent annual growth rate of 2% since 2008. Regrettably, the actual growth rate has only been 1% per year, falling significantly short of the target. If this trend persists, not only will the target remain unmet by 2040, but the recycling rate will continue to lag behind, exacerbating the issue (Pacheco-Torgal et al., 2020). Several authors have criticized the European Directive as ineffective. Arm et al. (2017) state that the Directive is very sensitive to how the legal definitions of waste and recovery are interpreted in the Member States. They also mention that the Directive does not distinguish between the various recovery processes and also that its weight-based approach favors large and heavy waste streams. Gálvez-Martos et al. (2018) criticized the use of weight percentages in the Directive because it may result in managers focusing on the dense mineral fractions rather than on other fractions with potentially higher environmental impact. These authors suggested that separation of targets per fraction should be included in the Directive. Other authors have examineed hazardous substances in CDW. Huang et al. (2017) reported a high content of hazardous substances in brick demolition wastes of a pesticide industrial plant. Knapp et al. (2017) analyzed the risk of accumulation and dispersion of hazardous substances, reporting that, in what concerns CDW, most heavy metal concentration complied with limit values, except for HOI and PAHs, highlighting the importance of a careful separation to avoid contamination. This information underlines that assessment methodologies need to focus not only on recycling rates but also on the risks to human health and the environment posed by the accumulation and dispersion of contaminants. Deetman et al. (2020) devised a model projecting that by 2050, recycled building materials may meet only 55% of the construction-related demand for copper, wood, and

steel. However, for other materials like aluminum, scrap availability could be higher, potentially fulfilling 71% of new demand. Despite this, in most regions, urban mining is unlikely to suffice in meeting the escalating demand for construction materials. Purchase et al. (2021) conducted an exhaustive literature review, unveiling the multifaceted barriers hindering the implementation of CE principles within the construction and demolition (C&D) waste sectors. These barriers can be distilled into five primary domains: legal, technical, social, behavioral, and economic aspects. Within this comprehensive framework, the study identified critical obstacles, including policy and governance constraints, permitting complexities, technological limitations, quality standard discrepancies, information accessibility gaps, and initial implementation costs. Furthermore, from the perspective of contractors, challenges predominantly center around C&D waste dismantling, segregation, onsite sorting, transportation, and local recovery processes. These challenges are particularly pronounced for small-scale enterprises, amplifying the urgency for tailored solutions and support mechanisms. A survey by Mohammed et al. (2022) with 220 Malaysian construction professionals revealed that policy-related factors have minimal impact on the relationship between current waste generation practices and sustainable construction waste management. The findings emphasize the importance of adopting preventive measures to reduce construction waste, which is vital for enhancing profitability in the industry.

Oluleye et al. (2022) investigated barriers to CE adoption in built construction industry (BCI) waste management. Through a comprehensive literature review and systems thinking, they identified 33 barriers categorized into seven groups (Fig. 1.1). Theoretical insights highlight the complexity of these barriers, emphasizing the importance of focusing on built construction and demolition waste (BCDW) management. Practical recommendations advocate for integrated strategies to overcome these

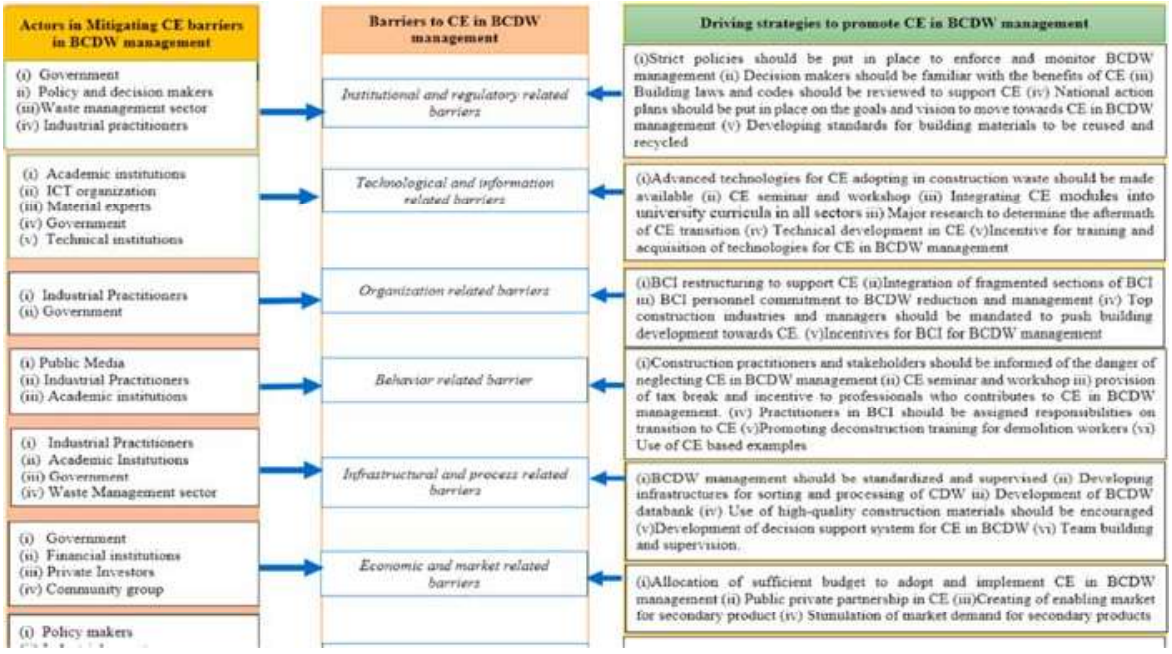


Figure 1.1 Implementation strategies to advance CE adoption in BCDW management. Reproduced from Oluleye et al. (2022).

obstacles. The study underscores the need for collaborative efforts to address these challenges, aiming to advance sustainable production and waste management in both the BCI and urban sectors.

Elshaboury et al. (2022) conducted a comprehensive bibliometric search using the Scopus database, uncovering 996 publications spanning from 2001 to 2021. Their findings reveal a notable evolution in the field of CDW management, marked by a significant surge in publishing output since 2006, which is characterized by a multidisciplinary and multiregional approach. Additionally, the study identifies key emerging research topics such as estimation and quantification, comprehensive analysis and assessment, environmental impacts, performance and behavior tests, management plans, diversion practices, and emerging technologies in CDW management.

Zhang et al. (2022) assessed the maturity of CDW management across European Member States (EMS), revealing notable disparities among countries. Generally, those in North-Western Europe demonstrate superior practices. The evaluation encompasses CDW generation, recovery, and landfill rates, highlighting that while the EU28 collectively achieves satisfactory recovery rates and minimal landfill usage, advancements in waste prevention are lacking. The study outlines the following pathways to augment the circularity of the construction sector in the EU:

1. Prevention: Prioritize reducing CDW generation to enhance circularity, focusing on indicators such as minimizing raw material extraction and waste mass.
2. Reuse preparation: Explore opportunities for reusing components and materials from demolished buildings, supported by initiatives like ReMark and Revolve standards. Future growth potential lies in technological innovation and standardization.
3. Recycling: Concentrate on high-value recycling to promote circularity, tackling challenges like onsite waste separation and ensuring the cost-effectiveness of recycling systems.
4. Downcycling: Recognize downcycling as a primary current method for CDW management, especially in road-base construction. Improve practices in countries with high landfill rates while encouraging cost-effective recycling in others.
5. Landfill reduction: Strive to eliminate the landfilling of mineral due to its recoverability. Address the higher landfilling rates for nonmineral waste by transitioning to downcycling or alternative recovery methods.

Moschen-Schimek et al. (2023) discussed challenges related to interpreting construction and demolition waste recovery rates (CDW RR) data from EUROSTAT (Fig. 1.2), highlighting issues such as undefined backfilling activities and inconsistent data collection methods. The study recommends cross-referencing reported data with national waste management institutions, establishing precise definitions for backfilling, and developing standardized EU-wide quantification models. Enhancing the quality of CDW data through uniform collection methods and clear coding is essential for effective waste management planning. These measures are crucial for improving the effectiveness, comparability, and reliability of CDW RR, thus promoting sustainable CE practices.

Bao and Lu (2023) investigated the correlation between economic development and construction waste generation across 27 European economies spanning from 2004 to 2018. Their analysis confirms a pattern: with increasing GDP per capita, construction waste generation initially escalates before gradually declining. This observation

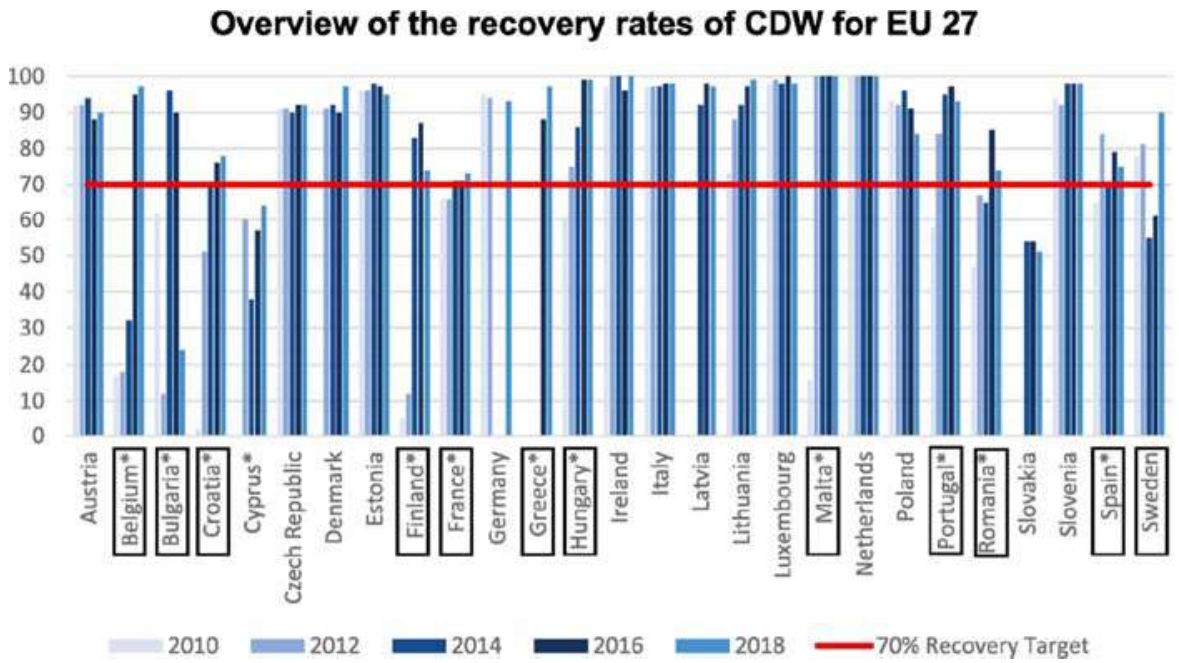


Figure 1.2 Overview of the recovery rates (RRs) of construction and demolition waste (CDW) for EU 27 published on EUROSTAT (2020) and the recovery target of 70% (*red line*); countries with RRs below 70% in 2010 are marked with *; CSCs (case study countries) are marked in *black*. Moschen-Schimek et al. (2023).

indicates a nuanced relationship in which economic advancement correlates with both exacerbating and subsequently ameliorating environmental degradation stemming from construction waste. Nevertheless, the study duly recognizes constraints stemming from data availability and aggregation, underscoring the imperative for future research endeavors to delve deeper into understanding this intricate dynamic. Zhang et al. (2023) conducted a study modeling the impact of recent construction innovations on concrete debris recycling in China. Despite advancements that enhance recycling rates and environmental sustainability, the adoption of these innovative technologies remains limited. The authors propose that regulators prioritize the use of financial incentives to promote diverse recycling activities, optimizing the utilization of technology in construction. This approach aims to curtail the extraction of virgin resources, thereby fostering economic and environmental advantages. Van Oorschot et al. (2023) introduced an innovative approach for spatially explicit material flow analysis (MFA) of building materials. This method assesses the impact of building strategy scenarios and urbanization pathways on material stock and flow dynamics, as well as material-related greenhouse gas (GHG) emissions and land use. Their findings indicate that while construction materials contribute modestly to emissions compared to space heating, future emission reductions necessitate attention to material-related emissions. Strategies such as transitioning to biobased or circular construction could significantly reduce primary material demand and GHG emissions, although their effects may not be fully realized until after 2050 due to slow stock renewal rates. However, challenges such as land-intensive biobased material production and limited wood production capacity in densely populated areas persist. Among these strategies, circular building

emerges as the most favorable for lowering GHG emissions and land use impact; however, challenges like component reuse and steel frame quality must be addressed during the design phase. Nawaz et al. (2023) have not only identified but also supported significant gaps in construction waste management research. They highlight the necessity for collaborative governance and stakeholder involvement throughout the building project lifecycle as a crucial knowledge gap. Collaborative governance, enabling agreement-based decision-making among public and private sectors and stakeholders, is vital, given the complexity of construction waste recycling administration. Their study also underscores gaps related to the interplay between organizational recycling practices and individual behavior within specific businesses, emphasizing the need to understand psychological and behavioral norms. Furthermore, they emphasize the often overlooked aspect of social sustainability in assessing building waste treatment options. Lastly, they identify a gap in the adoption of new technologies in construction projects, urging further exploration to harness the potential of methodologies like building information modeling (BIM) and radio-frequency identification (RFID) for waste quantification during the design phase. Oluleye et al. (2023) conducted a systematic review exploring how artificial intelligence (AI) models can enhance systemic circularity in the building construction industry (BCI). The study analyzes the strengths, weaknesses, opportunities, and threats (SWOT) of AI algorithms in relation to CE solutions, identifying 13 key application areas, including materials selection, design for waste prevention, circular business models, waste recycling, and logistics optimization. Additionally, it highlights significant challenges and proposes potential solutions, leading to the development of a holistic framework for integrating AI models throughout the building lifecycle. Future research directions include deep reinforcement learning for circularity, AI in 3D printing, and the optimization of management infrastructure and circular business models, all aimed at promoting digital systemic circularity in the BCI. Jaoude and Srour (2024) presented an innovative master plan development framework aimed at optimizing the management of CDW. Their approach involves a thorough synthesis of thematic and comparative analyses of literature-derived data, bolstered by an analytic hierarchy process (AHP) supported by expert input. The resulting framework is then validated through practical application in a case study set in a developing nation. This comprehensive methodology offers a robust strategy for effectively addressing CDW challenges and promoting sustainable waste management practices. Cristobal-Garcia et al. (2024) conducted a comprehensive technoeconomic and environmental assessment of CDW management in the EU, focusing on individual material fractions, including soil. They reviewed CDW generation, composition, and treatment; examined management technologies; evaluated environmental impacts and costs; and explored the potential for improved CDW management while addressing economic and noneconomic barriers and stakeholder feedback. They found that preparing materials for reuse and recycling, particularly metals, achieves the highest GHG savings, whereas landfilling and incineration, except for wood and mineral wool, result in the highest GHG burdens. Their study considered two scenarios: maximum recycling and a combination of reuse and recycling, with the latter offering greater CO_2 reductions and net cost savings. Overall, promoting reuse alongside recycling is recommended to maximize environmental and

economic benefits. The study also highlights that, except for wood, gypsum, and concrete waste, all CDW fractions can significantly contribute to GHG reductions at a cost below the current CO_2 price.

The literature review in this chapter highlights the complex barriers obstructing the adoption of CE principles in the construction and demolition waste sectors. While efforts have been made to pinpoint obstacles such as policy, technology, and economic factors, collaborative approaches are essential to surmount these challenges and propel sustainable waste management forward. Interestingly, policy-related factors exert minimal influence on sustainable construction waste management practices, underscoring the urgency of proactive measures to curb waste generation within the industry. Projections regarding resource availability suggest a shortfall in meeting construction material demand through recycled sources by 2050, necessitating innovative solutions and effective resource management strategies. Furthermore, regional disparities in CDW management across EMS underline the necessity for customized approaches to enhance circularity within the construction sector. Crucially, enhancing data quality and establishing clear definitions are imperative for effective waste management planning and the advancement of sustainable CE practices. While technological innovations offer promise for improving recycling rates, regulatory support is indispensable to incentivize adoption and optimize efficiency, thereby fostering both economic and environmental benefits. Lastly, identified knowledge gaps emphasize the critical importance of collaborative governance, stakeholder engagement, and a comprehensive understanding of organizational practices, individual behavior, and social sustainability for advancing waste management practices in the construction industry.

1.3 Outline of the book

This book provides an updated state-of-the-art review on advances in construction and demolition waste management. The first part encompasses digital technologies and managing of demolition waste (Chapters 2–6).

Chapter 2 explores regulations and policies concerning CDW in China, Japan, the United Kingdom, and Australia. It identifies current limitations and proposes strategies to maximize the utilization of CDW in diverse construction activities.

Chapter 3 aims to analyze the challenges of implementing CE principles in the construction industry and to propose circular solutions along with future trends. The challenges are categorized using the PESTLE framework, encompassing political/legal, economic, social, technological, and environmental dimensions. Each challenge is thoroughly discussed, with examples and references that contextualize the analysis and support recommendations for innovative circular approaches. The chapter also outlines medium- and long-term strategies for achieving zero-waste goals within the sector.

Chapter 4 presents a machine-learning-based system designed to improve the localization and classification of CDW fragments, aiming to enhance industrial sorting efficiency and promote environmental sustainability. Using U-Net and ResNet models for advanced classification, the methodology covers high-resolution image acquisition, preprocessing, feature extraction, data augmentation, and segmentation.

Chapter 5 highlights several critical challenges confronting the construction industry, including evolving user preferences, the ongoing digitization process, limited access to comprehensive materials data, and various technical obstacles. These factors collectively impede the industry's efforts to close the materials loop and transition toward more sustainable practices.

Chapter 6 examines the application of BIM and GIS (Geographic Information System) integration in construction and demolition waste minimization across project phases, emphasizing their potential and challenges. The study showcases the integration of BIM and GIS in creating digital material stock maps for a neighborhood in Belgrade, enhanced with pertinent CE data.

Part II encompasses processing and applications of recycled aggregates from construction and demolition wastes (Chapters 7–12).

Chapter 7 examines the current CDW management practices used by different countries and provides a detailed review of relevant legislation to clarify the key aspects of debris management. It also investigates innovative recycling methods, such as autogenous cleaning, air and hydraulic jigging technologies, and advanced dry recovery systems.

Chapter 8 reviews recent studies aimed at integrating fine aggregates from CDW into cost-effective and eco-friendly foam concrete products with targeted densities. It also examines the impact of CDW aggregates on the physical, mechanical, durability, and microstructural properties of foam concrete, alongside considerations of costs and carbon emissions.

Chapter 9 examines the mechanical and durability performance of recycled aggregate geopolymer concrete as a sustainable solution to rising CDW and cement consumption.

Chapter 10 provides the reader an overview of the behavior of self-compacting concrete (SCC) incorporating recycled aggregates (RA). It aims to demonstrate that the comprehensive mechanical properties of this concrete type can be effectively evaluated using a straightforward parameter such as porosity.

Chapter 11 examines the durability of recycled concrete, focusing on its role in sustainable construction. It discusses the use of recycled concrete aggregates (RCA), noting that while RCA slightly reduces strength due to higher porosity, it does not significantly impact durability. A well-designed mix with up to 50% RCA can enhance durability. The chapter also suggests better testing and quality control to support recycled concrete in high-grade applications.

Chapter 12 presents findings from water permeability tests on recycled compound concrete (RCC), investigating the impact of water-to-binder ratios and varying replacement rates of waste materials. Additionally, the chapter proposes a predictive method for estimating the permeability coefficient of RCC based on these findings.

Chapter 13 introduces the key concepts necessary for understanding the carbon capture potential of cementitious materials, with a particular focus on rendering mortars. Following this, a practical example will be presented to demonstrate how to evaluate this property effectively.

Chapter 14 reviews AI algorithms in the classification and composition of recycled aggregates and the prediction of the performance of recycled aggregate concrete,

particularly in forecasting durability attributes such as carbonation depth and chloride diffusion.

Environmental issues affecting recycled aggregates from construction and demolition waste are the subject of Part III (Chapters 15 and 16).

Chapter 15 provides general guidance for applying life-cycle assessment (LCA) to CDW recycling, addressing critical points and ongoing discussions within the LCA community. It includes a case study comparing advanced and conventional CDW recycling methods, with a particular emphasis on sensitivity and uncertainty analyses.

Chapter 16 presents a model based on BIM and the LCA technique to simulate the effects on waste generation caused by the selection and design of building elements. The types and quantities of CDW can be automatically predicted during the design stage. Furthermore, the environmental impact of alternative CDW management scenarios, such as recycling and disposal, can be simulated.

Chapter 17 serves as a comprehensive resource for professionals involved in managing mercury-contaminated CDWs and debris from mining sites, offering practical insights and recommendations to ensure both occupational safety and health in hazardous work environments and sustainable environmental remediation strategies.

Chapter 18 highlights the challenges construction professionals encounter in identifying and managing hazardous CDW. These challenges include vague classifications in the European Waste Catalog, time-consuming predemolition audits, leaching thresholds designed solely for landfilling, uncertainty over the applicability of REACH (Registration, Evaluation, Authorization of CHemicals) limits to older materials, and the scarcity or high cost of hazardous waste landfills.

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