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ADVANCES IN CONSTRUCTION AND DEMOLITION WASTE RECYCLING

MANAGEMENT, PROCESSING AND ENVIRONMENTAL ASSESSMENT

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Introduction to advances in construction and demolition waste

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1.1 Resource efficiency and the circular economy

World Business Council for Sustainable Development estimates that by 2050 a fourfold to 10-fold increase in resource efficiency will be needed (COM, 571). Allwood et al. (2011) recognizes that part of the problem is related to the fact that so far researchers have paid too little attention to the crucial issue of material efficiency. The truth is that there are still abundant resources to supply the construction industry (Pacheco-Torgal and Labrincha, 2013); still it is worth remembering the worrying environmental impacts caused by the extraction of nonrenewable raw materials, including extensive deforestation, top-soil loss, air pollution, and pollution of water reserves that will further aggravate the biodiversity loss boundary. On average for every ton of mined materials more than 85% became waste, for several it is more than 99% (Pacheco-Torgal and Jalali, 2011). Over the last century, the material consumption increased by a factor of around 10 and as a result human beings currently uses almost 60 billion tons (Gt) of materials per year (Krausmann et al., 2009). This dramatic increase has resulted in an accumulation of 792 Gt of materials within in-use stocks of buildings, buildings, infrastructure, and other manufactured goods (Krausmann et al., 2017). To make things worse some forecasts (Allwood et al., 2011) show that the demand for materials by 2050 will at least double the current levels. 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, 2011b) 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, 2011a) proposes a new pathway to action on resource efficiency involving all key stakeholders, sets several milestones to 2030 (recycling 65% of municipal waste; 75% of packaging waste; and reduce landfill to a 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. The Roadmap to a Resource Efficient Europe shows the importance of resource efficiency on the building sector which is clearly expressed by the milestone: "By 2020 the renovation and construction of buildings and infrastructure will be made to high resource efficiency levels. The life-cycle approach will be widely applied; all new buildings will be nearly zero-energy and highly material efficient and policies for renovating the existing building stock will be in place so that it is cost-efficiently refurbished at a rate of 2% per year.

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70% of nonhazardous construction and demolition waste (CDW) will be recycled" (COM, 2011a). An important concept inserted in the Europe 2020 Strategy for smart, sustainable and inclusive growth is the circular economy (CE) (COM, 2014; EC, 2015). Huysman et al. (2017) cites 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". Another definition states that the CE is "*an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts toward the use of renewable energy, eliminates the use of toxic chemicals impairing reuse, and aims at eliminating waste through the superior design of materials, products, systems, and business models*" (Ellen MacArthur Foundation, 2016). The Japanese government introduced the material-cycle society vision in 2000 involving several laws based on the three R's (reduce, reuse, recycle) principle. More recently, Cramer (2017) describe the raw materials transition in the Amsterdam Metropolitan Area of and highlights the need to advance on the 10 R's of the circularity ladder as a way to create more value. The evolution of CE scientific knowledge shows that an explosion took place in several countries since 2014. Results show that China produces the highest number of CE publications, yet EU-28 takes the lead if seen as a whole entity. These authors claim that is related to the policies introduced both in China and in EU concerning the promotion of the CE. The results also show that on this important field USA strangely shows a disappointing performance producing much less publications than UK, Germany, or even the Netherlands. Moreno and García-Álvarez (2018) developed a composite Resource-Efficiency Capacity Index based on the calculation of 29 indicators classified into three dimensions according to the Roadmap to a Resource Efficient Europe. Accordingly, they present an assessment of the 28 European members showing that the worst results are obtained for Cyprus, Slovakia, Malta, Poland, and Lithuania while the top performers are Denmark, Sweden, Finland, Germany, and Austria. Of course some authors warn about the problems associated to recycling high waste content. Lee et al. (2014) warned that full implementation of European waste legislation will increase unwanted micro-pollutants recycling. The studies of Knapp et al. (2017) confirm this problem because they showed that certain contaminants can be critical. These authors state that regulations for material recycling are required to assure adequate quality control measures. Also, although the concept of CE is already being enforced by several countries some authors showed that there are several limits and challenges in the concept in light of environmental sustainability. Several authors have described several barriers that could hinder successful implementation of the CE. Mittal and Sangwan (2014) mention "weak legislation and law enforcement, uncertain future legislation, low public pressure, high short-term costs, uncertain benefits, low customer demand, trade-offs, low top management commitment, lack of organizational resources, technological risk, lack of awareness/information." For Mangla et al. (2017) the most important are appropriate methods, tools, techniques, and indicators to cleaner production practices. Ritzén and Sandström (2017) have listed the following ones: "measuring financial benefits of CE, 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." More recently 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 inter organizational and inter-sectoral material and energy flows."

1.2 Construction and demolition waste recycling

Following the general CE concepts mentioned in the section above it is worth mentioning the Leising et al. (2018) definition on the CE for the buildings sector as "*A life-cycle approach that optimizes the buildings' useful lifetime, integrating the end-of-life phase in the design and uses new ownership models where materials are only temporarily stored in the building that acts as a material bank.*" Recent studies have focused on the need to prioritize barriers to adopt CE in CDW management (Table 1.1).

In an interesting case-study Yuan (2017) analyzed the barriers and countermeasures for managing CDW in Shenzhen (China) by reporting the following ones: "Lack of mature regulatory environment for managing C&D waste, separate involvement of multiple government departments in different C&D waste management processes without a leading department, lack of fundamental data in C&D waste, insufficient attention paid to waste management in construction projects, slow pace of C&D waste recycling factories toward growth." Stephan and Athanassiadis (2018) used a stock-driven and bottom-up model which was used to quantify and map the replacement flows for all buildings in the City of Melbourne, providing estimations on the materials urban authorities should focus on to establish reuse and recycling strategies. The results of these authors show that replacement flows represent, on average 26 kt/annum, 36 kg/(capita·annum), or 0.5 kg/ [m^2(gross floor area)·annum]. Currently, the European construction sector produces around 820 million tons/year of CDW, representing 50% of the total amount of total waste (EU, 2018). It is worth mentioning that the figures concerning the CDW generation per capita have a high geographical variation. So these figures must be viewed as lower estimates because in most countries this kind of wastes is illegally dumped. On the other hand, since different countries have different waste definitions and different reporting mechanisms the available data has a high uncertainty. Table 1.2 shows the minimum and maximum ranges for different waste categories in the field of construction and demolition.

The fact that concrete appears in a dominant position is just the consequence of the fact that twice as much concrete and mortar is used in construction—roughly 35 billion tons—as the total of all other industrial building materials (Van Damme, 2018). Fig. 1.1 shows how in the last 65 years, the amount of cement produced increased almost 34-fold but the population just increased threefold (Scrivener et al., 2018). This is not only related to the increase in global population that is projected to grow from the current 7.6 billion to 9 billion, being that 70% will live in cities but mostly because 3 billion people are expected to join the middle class, which will cause the largest and fastest demand for resources ever experienced in the world (Rios, 2018). According to the Revised Waste Framework Directive 2008/98/EC (WFD) the minimum recycling

Table 1.1 Summary of potential barriers to moving toward circular economy in C&D waste management (Mahpour, 2018)

Potential barrier
Ineffective C&D wastes dismantling, sorting, transporting, and recovering processes
Not green designing of construction projects
Using finitely recyclable construction materials
Overemphasizing recycle and nonenvironment-friendly methods during C&D phases of construction projects
Preferring off-site C&D wastes sorting/C&D wastes landfilling over on-site sorting due to lack of incentives
Inadequate policies and legal frameworks to manage C&D wastes as well as lack of supervision on C&D waste management
Lack of producer-based responsibility system in production of construction materials
Lack of clearly defined national goals, targets, and visions to move toward circular economy in C&D waste management
Inadequate awareness, understanding, and insight into circular economy in C&D waste management
Inherent complexity of transforming to circular economy in C&D waste management
Lack of integration of sustainable C&D waste management
Lack of empirically based literature on the barriers
Risk aversion
Undeveloped individuals' engagement
User preference for new construction materials over reused/recycled ones
Uncertain aftermaths of moving toward circular economy in C&D waste management
Nonstandardized C&D waste reduction reporting as well as lack of accessible data
Lack of funding to implement circular economy in C&D waste management
Tendency to manage cost & time rather than C&D wastes
Agency and ownership issues in C&D waste management
Lack of commitment by top urban managers to move toward circular economy in C&D waste management
Ineffective C&D waste management

Table 1.2 Construction and demolition waste composition (Gálvez-Martos et al., 2018)

Waste category	**%, Min-max range**
Concrete and masonry	40–84
Concrete	12–40
Masonry	8–54
Asphalt	4–26
Others (mineral)	2–9
Wood	2–4
Metal	0.2–4
Gypsum	0.2–0.4
Plastics	0.1–2
Miscellaneous	2–36

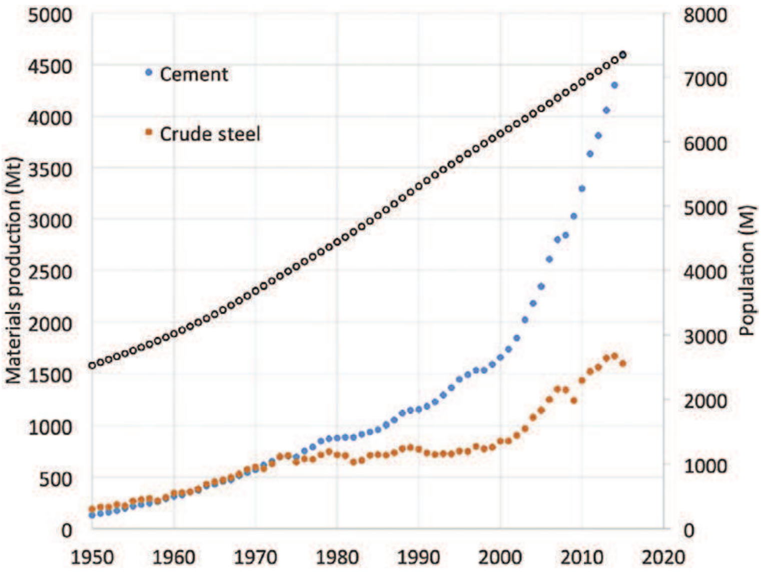

Fig. 1.1 Comparison of cement and crude steel production with population (Scrivener et al., 2018).

percentage of "*nonhazardous*" CDW *in the European Waste Catalogue*" by 2020 should be at least 70% by weight.

However, that would mean the recycling percentage had a growth of 2% per year since 2008. Unfortunately, it only grew 1% per year so the target will not be fulfilled by a long margin. Worse than that if the recycling rate keeps being just 1% then not only by 2040 the target be met, but also by 2050 the 100% recycling rate percentage of the zero waste scenario will be achieved. Also, several authors have criticized the European Directive as being ineffective. Arm et al. (2017) states that the Directive is very sensitive to how the legal definitions of waste and recovery are interpreted among 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) also criticize the use of weight percentages in the Directive because it may result on managers focusing on the dense mineral fractions rather than on other fractions with potentially higher potential environmental impact. These authors suggested that separation of targets per fraction should be included in the Directive. Since concrete constitute a major part of these wastes an important issue on CDW recycling is concerned with recycled aggregates (RAs). That explains why this book gives the issue of RA and special attention being addressed by almost 40% of the chapters, including the pretreatment aspects and the performance of concrete containing RA regulated by the European Standard EN 12,620:2013. An important aspect of the hazardous potential of RA is the leachability of chemicals. This issue is covered by the Study on Methodological Aspects Regarding Limit Values for Pollutants in Aggregates in the Context of the Possible Development of End-of-Waste Criteria Under the EU Waste Framework Directive

(Saveyn et al., 2014). This study, however, does not focus on other aspects of possible pollution such as emission of volatile substances from aggregates or radiation from aggregates. Other authors also investigate the case of CDW containing hazardous substances. Huang et al. (2017) reported a high content of hazardous substance on brick demolition wastes of a pesticide industrial plant. Knapp et al. (2017) analyzed the problem of risk of accumulation and dispersion of hazardous substances having reported that in what concerns CDW most heavy metal concentration complied with limit values with the exception of 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 for humans and the environment posed by accumulation and dispersion of contaminants. In recent years other books have been written in the field of recycling of CDW; still they are mostly dedicated to the performance of concrete with RAs and much less to important issues like waste management and environmental assessment, topics which deserve special attention.

1.3 Outline of the book

This book provides an updated state-of-the-art review on advances in CDW. The first part encompasses practices for CDW management (Chapters 2–8).

Chapter 2 gives an overview of recent CDW generation and recovery rates reported by some countries and regions; it examines CDW composition and quantification estimation ratios applicable at a regional level or construction project level; and appraises current and emerging C&DW management and quantification tools used for waste estimation, monitoring and auditing as well as location-based tools.

Chapter 3 analyzes the economic impacts related to the recycling of CDW. It presents an overview of the most recent results coming from the available economic and financial studies evaluating and comparing the production and use of recycled products from C&DW with the counterparts produced from virgin materials such as natural aggregates or natural concrete aggregates.

Chapter 4 aims to describe the most important specificities of CDW management. The description gives a closer look at site planning, the role of logistics, and on the most common policy and regulation practices around CDW.

Chapter 5 explores the ideal conditions to produce recycled gypsum from end-of-life gypsum, following the investigation within the European Life+ Project Gypsum to Gypsum LIFE11 ENV/BE/001039.

Chapter 6 surveys the demolition waste-DW generation rates for different types of buildings by conducting on-site surveys immediately before demolition in order to collect adequate and reliable data. In addition, the effects of DW management strategies and of monitoring the behavior of workers on the actual generation of DW were analyzed.

Chapter 7 concerns the use of Building Information Modeling (BIM) to accommodate the various and changing perspectives on CDW in order to facilitate the alignment of stakeholders and their actions toward higher precision, reliability, and efficiency in the representation and control of material flows in the built environment.

In Chapter 8, the Geographic Information System (GIS) is used in conjunction with Multicriteria Analysis (MCA) methods for the implementation of CDW management. Mapping illegal waste dumping sites was carried out in seven municipalities of the Metropolitan Region of Recife (MRR), Brazil; a classification of environmental risks from this dumping and location of suitable areas for installation of voluntary delivery points (VDP), CDW landfills, and recycling plants through spatial analysis were made.

Part II encompasses processing and applications of RAs from CDWs (Chapters 9–19).

Chapter 9 overviews various pretreatment techniques used to enhance the properties of RA, thus influencing the mechanical, interfacial, and durability-related attributes of resulting concretes. Both the physical methods (including mechanical grinding / churning, physical heating, and heat grinding) and chemical pretreatment techniques (including presoaking of RA in various acidic/basic solutions, bio-deposition, chemical grouting, carbonation, polymer treatment, and nano-modification of aggregate surface) have been comprehensively discussed.

Chapter 10 studies the technical feasibility of using *CDW* collected by Townsville City Council in Queensland, Australia, for pavement construction.

Chapter 11 discusses the research results in the field of RA-asphalt mixtures. The chapter also explains why RAs remain unpopular as acceptable materials in HMA production, discussing various treatments previously suggested for RA mixtures and also identifying future trends in the research of RA-asphalt pavements.

Chapter 12 investigates the state of the art on innovative and sustainable self-compacting concrete prepared with coarse and fine recycled concrete aggregates (RCAs) (up to 100% of the total amount of aggregates). Fresh state behavior is presented and related to the hardened state and durability characteristics.

Chapter 13 describes the influence on the properties of the fresh and hardened state of recycled HPC by different types of RAs, produced from concrete, ceramic, and mixed waste.

Chapter 14 summarizes the degree of influence of the different curing conditions on the properties of recycled concrete.

Chapter 15 covers the long-term behavior of concretes manufactured with coarse RCAs, discussing their long-term compressive, flexural, and splitting tensile strength, elastic modulus, water absorption, air/water permeability, chloride permeability, carbonation resistance, frost resistance, as well as their creep, shrinkage, and fatigue properties based on the results of studies reported in the literature.

Chapter 16 provides a review of the more relevant studies and the different applications of ceramic RAs in construction. Further, the structural ceramic waste in the manufacturing of concrete used in prestressed joists has been studied.

Chapter 17 studies the partial replacement of Portland cement blended with ceramic waste powder.

Chapter 18 analyzes the use of microbially induced carbonate precipitation (by using *Bacillus sphaericus*) to improve the quality of mixed and ceramic RAs.

Chapter 19 addresses the performance of RA geopolymer concrete including both properties and durability.

Environmental issues affecting RAs from CDW are the subject of Part II (Chapters 20–26).

Chapter 20 is concerned with the detection of asbestos in CDW. It includes innovative analytical tools, based on micro-X-ray fluorescence and hyperspectral imaging, to be applied both "in-situ" and at processing plant scale.

Chapter 21 reviews the leaching performance of RA. Leaching mechanisms are explained and exemplified as a function of pH. The effect of aging by carbonation and the factors that impact long-term leaching are shown.

Chapter 22 analyzes the environmental impact of CDW in urbanization projects. Three urbanization projects are evaluated from a dual perspective: both environmental and economic. An economic and environmental analysis using the carbon footprint indicator is also added through the traditional model for quantification and management of CDW.

Chapter 23 is a brief overview of liquid radioactive waste and the CDW properties are given, and the results of radionuclide removal achieved so are summarized and discussed. Knowledge gaps and needs for further studies are identified.

Chapter 24 deals with the life-cycle assessment of concrete production process. Concrete mixtures prepared with CDW at different sites are investigated to compare the environmental and energy impacts related to their production with mixtures made of natural aggregates.

Chapter 25 analyzes and compares the environmental impact assessment of concrete building blocks manufactured with RCAs-recycled aggregate concrete (RAC) blocks, using the life-cycle assessment (LCA) methodology.

By using an environmental (LCA) and an economic (LCC) analysis to compare different end-of-life alternatives for CDW, Chapter 26 highlights the environmental and economic drivers in CDW management.

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