

# Eco-efficient construction and building materials

Life cycle assessment (LCA),  
eco-labelling and case studies

Edited by F. Pacheco-Torgal, L. F. Cabeza,  
J. Labrincha and A. de Magalhães

Determining the life cycle of eco-efficient construction materials is of critical importance to professionals in the construction industry. Life cycle assessment (LCA) is an assessment of the environmental impacts of a given material from cradle to grave. This book provides a thorough overview of the LCA and eco-labelling of eco-efficient construction and building materials.

Part I provides an introduction to the environmental impact of construction and building materials, LCA, eco-labelling, and procurement. Topics covered in this section include mineral resource depletion assessment, LCA of sustainable building materials, and the strengths and weaknesses of LCA in the building sector. Part I describes the use of LCA methodology in developing eco-labels for construction and building materials, outlines the EU Ecolabel scheme, and the Environmental Product Declaration (EPD) labelling of construction and building materials. This part also provides an overview of the shortcomings of eco-labelling of construction and building materials, and the green public procurement (GPP) of construction and building materials. Part II assesses the environmental impact of construction and building materials. This section analyses the environmental impact of conventional and 'green' cement production, describes the LCA of concrete made using recycled concrete or natural aggregates, the LCA of building thermal insulation materials, phase change materials (PCMs), road pavement materials and wood-based building materials, and discusses the environmental impact of adhesives. Part III considers the environmental impact of particular types of structure. This section includes a comparison of the environmental impact of reinforced concrete and wooden structures, assesses the sustainability of prefabricated buildings, the LCA of green facades and living wall systems, and the environmental and economic impacts of cladding systems for green buildings. It also covers the LCA of windows and window materials, ultra high performance concrete (UHPC) structures, and the LCA of fibre reinforced polymer (FRP) composites in civil applications.

*Eco-efficient construction and building materials* provides a comprehensive insight into all aspects of the LCA and eco-labelling of eco-efficient construction and building materials, and is an essential text for construction industry professionals, researchers, academics, postgraduate and undergraduate university students.

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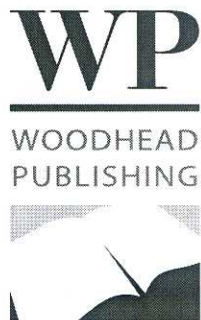
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# Introduction to the environmental impact of construction and building materials

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**Abstract:** Earth's natural resources are finite and face increasing human pressure. Over the last few decades, concern has been growing about resource efficiency and the environmental impact of material consumption. The construction industry is responsible for the consumption of a relevant part of all produced materials, however, only recently has this industry started to worry about its environmental impacts. This chapter highlights relevant landmarks on sustainable development, materials efficiency and on the assessment of the environmental impact of construction products. An overview on the European Construction Products Regulation (CPR) enforced since the 1 July 2013 is given followed by an outline of the book.

**Key words:** sustainable development, materials efficiency, environmental impact, LCA, eco-labels, product self-declarations.

## 1.1 Introduction

Four decades ago, several investigators used a computer model based on the fixed-stock paradigm to study the interactions between population, food production, industrial production, pollution and the consumption of non-renewable resources. They predicted that during the 21st century, the Earth's capacity would be exhausted, resulting in the collapse of human civilisation as we know it (Meadows *et al.*, 1972). Two decades later, an update of this study was published showing that some limits had already been crossed (Meadows *et al.*, 1992). Whilst the particular assumptions and predictions of such studies have been questioned, there is general agreement that many of the Earth's key resources are finite and must be conserved. As a consequence, the concept of 'sustainable development' gained international recognition through the landmark Brundtland Report 'Our common future' (Brundtland, 1987).

Some authors (Clayton, 2001; Choi and Patten, 2001) have argued that 'sustainable development' is an oxymoron: we cannot have development/growth for the entire world population and at the same time, expect this development to be compatible with protection of the environment. The fact that there have been serious environmental disasters in Europe, such as Stava (1985), Aznalcollar (1998), Baia Borsa (2000) and Kolontar (2010),

despite the region's relatively high environmental standards, illustrates this problem. The challenge is also highlighted by continued growth in materials use. Europe has the world's highest net imports of resources per person, and its open economy relies heavily on imported raw materials and energy. In 2007 the total amount of material directly used in the EU economy was more than 8 billion tonnes (COM, 2011a).

It has been estimated that global materials use increased eight-fold in the last century and that current usage is almost 60 billion tons (Gt) of materials per year (Krausmann *et al.*, 2009). Despite this huge historic growth, some authors predict that materials demand will double by 2050 (Allwood *et al.*, 2011). It is important to note that 40% of all materials are used by the construction industry (Kulatunga *et al.*, 2006). The construction industry is expected to continue to grow rapidly. As an example, it is estimated that India will invest US\$ 1 trillion in infrastructure between 2012 and 2017 (Chakraborty *et al.*, 2011). In the USA, where around 27% of all highway bridges are in need of repair or replacement, the needs for infrastructure rehabilitation alone are estimated to be over US\$ 1.6 trillion during the next five years, (Davalos, 2012). Wang *et al.* (2010) have estimated that construction activities in China consume approximately 40% of its total natural resources and around 40% of its energy and that the country will need 40 billion square metres of combined residential and commercial floor space over the next 20 years – equivalent to adding one New York City every two years (Pacheco-Torgal and Labrincha, 2013a; Pacheco-Torgal and Jalali, 2011).

The World Business Council for Sustainable Development estimates that by 2050, a four- to ten-fold increase in resource efficiency will be needed (COM, 2011a). Over the last few decades, concern has been growing about resource efficiency and the environmental impact of material consumption. As a result, the term 'green materials' became very popular in the construction sector. However, it was not until 2012 that the first life cycle assessment (LCA) investigations into standard structural concrete made using Portland cement started to become available (Van den Heede and De Belie, 2012; Habert *et al.*, 2012). This is despite the fact that it is the most used construction material with output currently about 10 km<sup>3</sup>/year. In comparison, the amount of fired clay, timber, and steel used in construction represents about 2, 1.3 and 0.1 km<sup>3</sup>, respectively (Flatt *et al.*, 2012). There is still much to investigate concerning the LCA of this material, for example incorporating recent nano and biotech approaches (Jayapalan *et al.*, 2013; Pacheco-Torgal and Labrincha, 2013b).

## 1.2 Environmental impact assessment

The methodology used to assess the environmental impacts of a given material is known as 'life cycle assessment' (LCA) and 'includes the

complete life cycle of the product, process or activity, i.e., the extraction and processing of raw materials, manufacturing, transportation and distribution, use, maintenance, recycling, reuse and final disposal' (SETAC, 1993). The application of LCA has been regulated internationally since 1996 under the International Standards Organisation (ISO) which classifies the existing environmental labels into three typologies – types I (eco-labels, ISO 14024), type II (product self-declarations, ISO 14021), and type III (EPDs, ISO 14025). It should be noted that in 2012, the DG Environment published the draft of a harmonised methodology for calculating of the environmental footprint of products (Del Borghi, 2013). Since the first eco-label, the German Blue Angel, was created in 1978, several others have appeared. However, some authors (Rajagopalan *et al.*, 2012) argue that 'the labelling of green materials is confusing and that consumers are suspicious about the environmental claims of manufacturers.'

Hauschild *et al.* (2013) state that the LCA standard ISO 14040-44 is rather generalised and non-specific in its requirements and offers little help to the LCA practitioner in making choices. The weighting process related to decision making as to which environmental impacts are most significant for the process or product in question remains a controversial and inexact science (Johnsen and Løkke, 2013). Other issues also remain as open questions in the LCA methodology (Feifel *et al.*, 2010).

Other important subjects must also be taken into account in considering the future environmental impact of construction and building materials. For example, it remains to be seen if the benefits of recycling should be credited to the primary producer or to the user of recycled materials (Huang *et al.*, 2013; Chen *et al.*, 2010). This is a crucial issue in the context of the Revised Waste Framework Directive (WFD) 2008/98/EC (EU, 2008) which established that by 2020, the minimum recycling percentage of 'non-hazardous' construction and demolition wastes should be at least 70% by weight (Pacheco-Torgal *et al.*, 2013). Improving the reuse of raw materials through greater 'industrial symbiosis' across the EU could save €1.4bn a year and generate €1.6bn in sales (COM, 2011a).

The simplifications of LCAs are unlikely to cope well with the increased importance of the environmental impacts of construction and building materials in the context of low energy buildings. (Kellenberger and Althaus, 2009; Blengini and Di Carlo, 2010). It should be noted that higher energy efficiency in new and existing buildings is the key for transformation of the EU's energy system (COM, 2011b). According to the European Energy Performance of Buildings Directive (EU, 2010), all new constructions will have to be nearly zero-energy by 31 December 2020.

Current labelling schemes are only concerned with short term volatile organic compound emissions from building materials. Research on long-term emissions is therefore needed to reduce the level of uncertainty (Skaar

and Jørgensen, 2012). It should be remembered that more than 100,000 new chemical compounds have been developed since 1939 and insufficient information exists for health assessments of 95% of the chemicals used in construction products (Pacheco-Torgal *et al.*, 2012).

It is also significant that product replacement may take place over a very short period of time as occupant behaviour is influenced by societal trends. Therefore estimation methods capable of capturing consumer behaviour are a necessary step towards modelling over a lifetime (Aktas and Bilec, 2011). In future, it will be necessary to apply dynamic methods to the LCI or LCIA (Collinge *et al.*, 2013).

### 1.3 The European Construction Products Regulation (CPR)

The European Union has been in the lead on seven important initiatives to address smart, sustainable and inclusive growth up to 2020 and beyond. One of these: 'A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy' (European Commission, 2010), highlights the importance of increasing resource efficiency as the key to major economic opportunities, improving productivity, driving down costs and boosting competitiveness.

The EU has recently passed regulations that will make the environmental assessment of construction and building materials mandatory. On 9 March 2011 the European Union approved Regulation 305/2011 (EU, 2011), the CPR, which replaced Directive 89/106/EEC, already amended by Directive 1993/68/EEC, known as the Construction Products Directive (CPD). The new CPR was published in the *Official Journal of the European Union (OJEU)* on 4 April 2011. In accordance with Article 68, the CPR entered into force on 24 April, the 20th day following its publication in the *OJEU*. This includes Articles 1 and 2, 29 to 35, 39 to 55, 64, 67 and 68, and Annex IV. However, Articles 3 to 28, 36 to 38, 56 to 63, 65 and 66, as well as Annexes I, II, III and V, will apply from 1 July 2013. Therefore the CPR will be fully enforced without the requirement for any national legislation by 1 July 2013.

A regulation is defined as follows: 'Shall have general application. It shall be binding in its entirety and directly applicable in all Member States'. The CPD statutes are 'binding, as to the result to be achieved, upon each Member State to which it is addressed, but shall leave to the national authorities the choice of form and methods'. This means that the UK, Ireland and Sweden will lose their 'opt-out' clause employed under the CPD period.

When the basic requirements of the CPR and CPD are compared, it may be seen that the CPR has a new requirement (No. 7 Sustainable use of

natural resources), and that No. 3 (Hygiene, health and the environment) and No. 4 (Safety and accessibility in use) have been refined. This means that commercialisation of construction materials in Europe beyond 2013 will be subject to mandatory environmental assessment. Updated literature will be needed to help the construction industry as this sector generates almost 10% of the European GDP and provides 20 million jobs, mainly in micro and small enterprises, thus playing an important role in the European economy (COM, 2012).

## 1.4 Outline of the book

This book covers several aspects of the environmental impacts of construction and building materials, including cases studies offering an overview of materials in the wider context of final in-use.

The first part encompasses an overview of relevant issues for LCA, eco-labelling and procurement (Chapters 2–9).

Chapter 2 concerns resource depletion. The scarcity of minerals is assessed in a static way through the reserves to production ratio as well as by a dynamics viewpoint through Hubbert peak models. This chapter includes a new methodology for abiotic resource depletion.

Chapter 3 covers LCA software tools.

Chapter 4 addresses the possibilities and limitations of LCA. It describes the methodological options that will potentially influence the results from the LCA.

Chapter 5 is concerned with LCA and eco-labels.

Chapter 6 describes the EU Eco-label and reviews its history, goals and statistics. Consideration is given to the criteria for obtaining a label. Special attention is given to the Eco-label 'product groups' which are of interest to the construction and building materials sector: floor coverings (hard, wood, textile), paints and varnishes.

Chapter 7 analyses the eco-label type III: Environmental Product Declaration (EPD) which is regulated by the ISO 14025. The methodological aspects of the EPD development process are described. Important EPD Programmes from around the world are provided as well as details on the product category rules (PCR) for construction and building materials. Three case studies of EPDs for the construction industry are presented (concrete, thermal insulation materials and wood boards).

Chapter 8 covers the shortcomings of eco-labelling.

Chapter 9 addresses green public procurement (GPP) which involves the incorporation of environmental requirements during the procurement of services and products by public authorities. It analyses the expansion of GPP into sustainable public procurement (SPP), where social and



sustainable development considerations are also integrated, and discusses the implementation of GPP/SPP in the construction sector.

The environmental impact of construction and building materials are the subject of Part II (Chapters 10–16).

Chapter 10 analyses the environmental impact of cementitious materials. A detailed description of Portland cement production process is offered, including its main environmental impacts ( $\text{CO}_2$ ,  $\text{PM}_{10}$ ,  $\text{SO}_x$  and  $\text{NO}_x$  emissions). Future improvements (alternative fuels, energy efficiency, CCS technology, cement consumption efficiency) are described and descriptions of SCMs and their environmental impact are presented. The use of alternative binders is also considered, including alkali activated aluminosilicates, calcium sulfoaluminate cements, celitement and cements from magnesium silicates. The reduction of the environmental impact of cementitious materials through improvement of their mechanical strength is also addressed.

Chapter 11 offers an environmental assessment of structural concrete and presents LCA results for concretes with three different types of aggregate: natural gravel, natural crushed and recycled concrete aggregate. The influence of the transport phase and  $\text{CO}_2$  uptake during the life cycle of concrete structure is discussed.

Chapter 12 looks at thermal insulation materials and analysis carried out by using SimaPro and the Eco-indicator 99 software characterisation method. This chapter also includes an economic analysis of insulation materials.

Chapter 13 is concerned with the LCA of buildings including PCMs. It evaluates the environmental impact of using PCMs in building envelopes, using the impact assessment method Eco-Indicator 99 which is extracted from the database Eco-Invent 2009. Two different construction systems are assessed: conventional brick and alveolar brick based.

Chapter 14 reviews the LCA of wood-based building products and considers their manufacturing processes. It discusses design and building with wood and the material and energy flows associated with wood-based construction.

Chapter 15 is concerned with adhesives.

Chapter 16 closes Part II with a closer look at roadway pavements. Results on the LCA over a service period of 30 years for four different pavement types (two concrete pavements and two asphalt pavements) are presented. Environmental implications and green alternatives are discussed.

Part III (Chapters 17–23) deals with environmental impact of particular types of structure.

Chapter 17 compares the environmental strengths and weaknesses of wood and concrete in construction. The use of LCA for wood and concrete

buildings design is included. This chapter also includes a case study which compares the LCA of two buildings with the different structural materials (wood and concrete). Open source software, open LCA (GreeDeltaTD) was used for the inventory phase and Eco-indicator 99 was used in the assessment phase.

Chapter 18 reviews prefabricated technologies. Comparisons between prefabricated and non-prefabricated methods are made in relation to their economic, environmental and social impacts. This chapter also includes an environmental assessment of the main technologies used in prefabricating 161 school buildings in Catalonia, Spain, between 2002 and 2009 using a multi-criteria decision-making method.

Chapter 19 examines green wall systems and compares the environmental impact of a bare brick façade with four greening systems:

1. A conventional façade covered with a climber planted at the base of the façade (greened directly).
2. A conventional façade covered with a climber planted at the base of the façade using a stainless steel framework to create a cavity between foliage and façade (greened indirectly).
3. A conventional façade covered with a living wall system (LWS) based on planter boxes filled with potting soil.
4. A conventional façade covered with a living wall system based on felt layers and a conventional façade covered with a living wall system based on mineral wool.

Chapter 20 covers cladding systems. It gives a brief description of the use of the concept of eco-efficiency in the assessment of green cladding systems and presents a systematic assessment of an actual case study.

Chapter 21 compares LCA studies on the impacts of different framing materials with mixed results.

Chapter 22 deals with the LCA of ultra-high performance concrete (UHPC), using the software SimaPro and the Swiss ecoinvent database for life cycle inventory data. The chapter includes different applications of UHPC which are compared to conventional building materials: (a) high rise building columns; (b) five different hot rolled I-beams; (c) two traffic bridge design models and three footbridges.

Chapter 23 closes Part III and covers the LCA of fibre reinforced polymer (FRP) composites. Three LCA case studies from both the composites and civil engineering industries are presented. The first concerns three generic product types: (a) a double curvature monolithic panel, (b) a flat sandwich panel with core, and (c) a complex moulded component. The second is related to a pedestrian bridge in the Netherlands. In the third, FRP decks are examined by comparing the life cycle environmental performance, in carbon terms, with the conventional concrete option.

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