Introduction

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1.1 Repair and rehabilitation of concrete infrastructures on the context of sustainable development

Rockström et al. (2009) proposed an approach to global sustainability defining nine interdependent planetary boundaries within which they expect that humanity can operate safely. This include:

1. climate change (CO₂ concentration in the atmosphere <350 ppm and/or a maximum change of +1 W/m² in radiative forcing);
2. ocean acidification (mean surface seawater saturation state with respect to aragonite ≥ 80% of pre-industrial levels);
3. stratospheric ozone (<5% reduction in O₃ concentration from pre-industrial level of 290 Dobson Units);
4. biogeochemical nitrogen (N) cycle (limit industrial and agricultural fixation of N₂ to 35 Tg N/yr) and phosphorus (P) cycle (annual P inflow to oceans not to exceed 10 times the natural background weathering of P);
5. global freshwater use (<4000 km³/yr of consumptive use of runoff resources);
6. land system change (<15% of the ice-free land surface under cropland);
7. the rate at which biological diversity is lost (annual rate of <10 extinctions per million species).

Two additional planetary boundaries for which a boundary level was not yet determined are: chemical pollution and atmospheric aerosol loading. According to the authors, the “transgression one or more planetary boundaries may be deleterious or even catastrophic due to the risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental- to planetary-scale systems”. These authors estimated that humanity has already transgressed three planetary boundaries for changes to the global nitrogen cycle, the rate of biodiversity loss and, above all, climate change (Hansen et al., 2013, 2016, 2017). Most unfortunately, the repeated fiascos of the so-called Conference of Parties (COPs) in Warsaw (COP-19) in 2013, Lima (COP-20) in 2014, Paris (COP-21) in 2015 and, most recently, Marrakech (COP-22) in November of 2016 to agree on important reductions on greenhouse gas emissions only worsened the climate change scenario. The major problem being the fact that the major emission emitters: China, US and India, do not accept severe cuts. If the position of China and India is understandable from an economic view, the US is not, because it is a well-developed economy, and
on a per-capita historical basis, the U.S. is 10 times more accountable than China and 25 times more accountable than India for the increase of atmospheric CO$_2$ above its preindustrial level (Hansen and Sato, 2016).

As a consequence of this worrying status, it remains crucial to act in order to address those problems in a context in which urban human population is growing exponentially. Each day there are now about 200,000 new inhabitants on planet Earth and in the next decades human population will almost double, increasing from approximately 3.4 billion in 2009 to 6.4 billion in 2050 (WHO, 2014). As a consequence, recent estimates on urban expansion suggests that until 2030 a high probability exists (over 75%) that urban land cover will increase by 1.2 million square kilometer (Seto et al., 2012). This overpopulation will require new infrastructure and will put increase pressure on the existent infrastructures.

Concrete infrastructure encompasses bridges, piers, pipelines, dams, pavements, or buildings that are crucial to services and economic activities of modern civilization. Unfortunately, concrete deteriorates due to several causes including: mechanical deterioration from impact or excessive loading, or deterioration due to physical causes of erosion or shrinkage. More frequently, however, it deteriorates through chemical detrimental reactions when it is exposed to environmental conditions containing chlorides from seawater or from deicing salts, atmospheric carbon dioxide, or other aggressive media (Glasser et al., 2008).

The importance of concrete durability has been emphasized by Mora (2007), when he stated that increasing durability from 50 to 500 years would mean a reduction of its environmental impact by a factor of 10. Concrete infrastructure with low durability requires frequent maintenance and conservation operations and its integral replacement is associated with the consumption of huge amounts of raw materials and energy. Many of the degraded concrete infrastructures were built decades ago when little attention was given to durability issues (Hollaway, 2011). Deficient execution due to poor workmanship is also a relevant cause of premature degradation of concrete infrastructure and reinforcement corrosion (Costa and Appleton, 2002) and this cause is becoming increasingly relevant in recent decades (Elrakib and Arafa, 2012), relevant to the cost increase of workmanship. Additionally, the majority of technical standards and codes that deal with durability design and control of execution do not make any provisions for the assessment of concrete cover depth achieved in structures. This constitutes a serious gap, because failure to comply of the concrete cover depth with the specifications is one of the main causes of premature deterioration of reinforced concrete structures (Monteiro et al., 2015; de Medeiros et al., 2016).

Climate change is also increasingly responsible for the premature deterioration of concrete infrastructure. Not only due to occasional and extreme atmospheric events, but in a more frequent pattern due to concrete carbonation associated with the steady increase on CO$_2$ concentration (molecules of CO$_2$ for every one million molecules in the atmosphere) (Fig. 1.1). Its important to mention that 2016 was the first year with atmospheric CO$_2$ concentrations above 400 ppm all year round (Betts et al., 2016) and even if all the greenhouse gas emissions suddenly ceased, the amount already in the atmosphere would remain there for the next 100 years...
Wang et al. (2010) showed that additional carbonation-induced damage risks for the A1FI emission scenario (CO$_2$ concentrations increasing by more than 160% to 1000 ppm by 2100) are up to 16% higher if there are no changes to how concrete structures are designed or constructed. Stewart et al. (2011) found that carbonation-induced corrosion can increase by over 400% by 2100 for inland arid or temperate climates in Australia. Bastidas-Arteaga et al. (2013) noticed that climate change might reduce the time to failure of reinforced concrete structures by up to 31%. Talukdar and Banthia (2013) found that concrete structures that will be constructed in the year 2030, in areas where carbonation induced corrosion would be a concern (moderate humidity, higher temperatures and for a dry exposure class), structures are expected to show a reduction in serviceable lifespan due to climate change of approximately 15–20 years, with signs of damage being apparent within 40–45 years of construction. Since, in urban settings, CO$_2$ concentrations can be much higher than in nearby rural environments, and that urban areas are subject to increase temperature levels due to urban heat island effects, this means that concrete infrastructure located in urban areas are subject to more intense carbonation-damaging actions. According to Saha and Eckelman (2014), climate change will accelerate corrosion and degradation of concrete structures in Boston. By the year 2055, the chlorination-induced corrosion depth in concrete structures built in year 2000 may exceed the code-recommended protected cover thickness of 38 mm. For carbonation-induced corrosion, the
threshold year is 2077. Rehabilitation of concrete infrastructures to address future carbonation-induced corrosion under much-higher CO$_2$ concentrations, or any other climate change related deterioration action, can be considered in the context of urban adaptation. Fig. 1.2 shows a world map concerning the status of urban adaptation to climate change in areas with over one million inhabitants, each covering a total of 1.3 billion people. Many of the existing infrastructures will still be in use by 2030 and even in 2050 when climate change might have far more substantial impacts than today, meaning that repair and rehabilitation action will be needed to prevent premature degradation (Giordano, 2012). Worldwide concrete infrastructure repair rehabilitation needs are therefore enormous. In US there are more than 60,000 structurally deficient bridges. For China this number exceeds more than 80,000 bridges. In Europe in the next 10 years some 1500 railway bridges are expected to be strengthened, 4500 have to be replaced, and the deck of other additional 3000 bridges has to be replaced (Casas, 2015). Consequently, its costs are staggering. According to OECD, improving the world’s infrastructure will require an estimated $7 trillion/year USD (Kennedy and Corfee-Morlot, 2013).

In the US, the corrosion deterioration cost due to deicing and sea salt effects is estimated at over 150 billion dollars and infrastructure repair rehabilitation overall needs are estimated to be over 1.6 trillion dollars over the next years (Davalos, 2012). A climate-change induced acceleration of the corrosion process by only a few percent can result in increased maintenance and repair costs of hundreds of

**Figure 1.2** Map of global urban adaptation panel.
billion of dollars annually (Bastidas-Arteaga and Stewart, 2015). The annual cost of corrosion worldwide is already over 3% of the world’s Gross Domestic Product (GDP) (Bossio et al., 2015). In Europe, bridge maintenance repair and strengthening requires an annual budget of £215M, and that estimate does not include traffic management cost (Yan and Chouw, 2012). In US, costs related to wasted fuel and time loss due to traffic congestion are estimated between 50 and 100 billion dollars (Report, 2012; Schlangen and Sangadji, 2013). In the city of Hong Kong, more than 580,000 vehicles cross its 900 highway bridges on a daily basis (Pei et al., 2015). This traffic volume is expected to duplicate in the next decades. It can never be overemphasized that Earth’s populations are growing at a very fast pace and as a consequence in 2014 there will be 12,000 million vehicles on the road and by 2035 this number will increase to 2000 million and 2500 million by 2050 (Navigant Research, 2014). This means that concrete highways bridges will be subject to increase use and will reach the end of their service life sooner than expected and repair and rehabilitation costs will increase even further. The “Law of Fives” states that $1 spent on design and construction is equivalent to $5 spent as damage initiates, before it propagates; $25 once deterioration has begun to propagate, and $125 after extensive damage has occurred (Delatte, 2009). This concept highlights the importance acting as soon as possible to prevent concrete infrastructure reaching a level where extensive damage has occurred and the rehabilitation costs grow exponentially. This action is related to the assessment of the infrastructure performance, but monitoring activities are also costly and not all countries can afford it. In the US, bridges are inspected every 2 years (Rehman et al., 2016). The lack of regular inspections worsens the problem and contributes to premature infrastructure deterioration, thus leading to possible bridge failure with an inevitable loss of human lives. Its worth remembering that the 1967 failure of the Silver Bridge in Ohio caused 46 deaths, in 1981 the failure of the Hyatt Regency walkway in Kansas City failure caused 114 deaths and 216 were injured, and in 2001 the Entre Rios bridge in Portugal caused 59 deaths.


It is, by now, a standard that lags behind the state of the art on the field of repair and rehabilitation on concrete infrastructures. Bartuli et al. (2010) had already suggested an update of its content. Such an update is more necessary because a few years ago the European Union passed regulations concerning the
environmental performance of construction and building materials. On March 9, 2011, the European Union approved Regulation (EU) 305/2011, the Construction Products Regulation (CPR), that replaced Directive 89/106/EEC, already amended by Directive 1993/68/EEC, and known as the Construction Products Directive (CPD). When comparing the basic requirements of the CPR and CPD, one can see that the CPR has a new requirement: No. 7 (Sustainable use of natural resources), and also that No. 3 (Hygiene, health and the environment) and No. 4 (Safety and accessibility in use) have been refined. Meaning, since July 1, 2013, environmental assessment of construction materials in Europe it is mandatory for commercialization. Since some of the repair materials mentioned in the EN 1504 like polyurethane and epoxy have a high environmental impact (Pacheco-Torgal et al., 2012) the future revision of this standard will have to focus on more eco-efficient repair materials.

The methodology used to assess the environmental impacts of a given material or activity from cradle to grave is known as “Life Cycle Assessment” (LCA). It “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”. The application of LCA has been regulated internationally since 1996 under International Standards Organization (ISO) which classifies the existing environmental labels into three typologies—types I (eco-labels, ISO 14024), II (product self-declarations, ISO 14021), and III (EPD’s, ISO 14025) (Pacheco-Torgal et al., 2013).

The concept of eco-efficiency was first coined in the book “Changing course” (Schmidheiny, 1992) in the context of 1992 Earth Summit process. This concept includes “the development of products and services at competitive prices that meet the needs of humankind with quality of life, while progressively reducing their environmental impact and consumption of raw materials throughout their life cycle, to a level compatible with the capacity of the planet”. The eco-efficient repair and rehabilitation means to increase the service life of concrete infrastructure, and to use eco-efficient materials when possible, to design accounting for damaging effects due to climate change and also by taking account LCC and LCA. Thus greater economic and environmental efficiency can be achieved by designing infrastructure that is simultaneously low carbon and climate resilient (Pacheco-Torgal, 2014; Kennedy et al., 2014).

The purpose of this book is to make a contribution in this area. Other books have already been written about repair and rehabilitation of concrete infrastructures, but some books focus only on strengthening and rehabilitation using fiber reinforced polymers (FRP)—a material that has some durability shortcomings as can be seen on a chapter of Part 1 of this book. Others rely only on practical advice, unsuitable to researchers. None have a strong cover of innovative materials, to which this book dedicates a relevant part, nor do they dedicate even a minimum attention to repair design, accounting to climate change design effects or to LCC and LCA of repair and rehabilitation of concrete infrastructure like this one does.
1.2 Outline of the book

This book provides an updated, state-of-the-art review on eco-efficient repair and rehabilitation of concrete infrastructures.

The first part encompasses materials and technologies (Chapters 2–10):

Chapter 2, Service life estimation of concrete infrastructures, concerns service life estimation of concrete structures and their main mechanisms. They are described and critically reviewed in the light of properly analyzed experience for, and behavior of, actual reinforced concrete structures.

Chapter 3, Impact of climate change on the service life of concrete structures, discusses some effects of climatic variables on concrete durability and some scenarios of climate change. An example of a numerical application about the corrosion of reinforcements on the Brazilian coast is presented.

Chapter 4, Monitoring of reinforced concrete corrosion, presents an overview of the state of the art in using sensors for online monitoring of rebar corrosion inside reinforced concrete (RC) structures. It includes: current technologies for online monitoring of those structures, embeddable sensors for chloride concentration, pH, humidity, reference electrode, and other parameters, and then a case study of accelerated testing of embeddable sensors.

Chapter 5, Monitoring with optical fiber sensors, deals with the use of distributed optic fiber for the monitoring of concrete structures. An overview on optic fiber technologies is given and then a practical guide in order to select the appropriate optic fiber system for a given monitoring purpose, such as the crack detection or the strain measurement is suggested.

Chapter 6, Structural health monitoring through acoustic emission, covers the use of acoustic emission as a structural health monitoring technique to monitor the performance and integrity of the structure when subjected to fatigue loading.

Chapter 7, Durability problems of concrete structures rehabilitated with FRP, provides a review of the use of Fiber Reinforced Polymer-FRP composites for the strengthening/reparation of concrete structures. Special attention is paid to the durability of FRP’s in terms of their degradation causes and mechanisms; for resins, fibers, and the whole system.

Chapter 8, Field assessment of concrete structures rehabilitated with FRP, discusses several test methods to evaluate FRP, with a section to provide a relative assessment of each available test. The chapter closes by providing a section of the future of technology and application regarding FRP, with advice.

Chapter 9, Field assessment of a concrete bridge, presents a case study of the field assessment: visual inspection and load testing of a reinforced concrete bridge, with cracking caused by alkali-silica reaction. It encompasses the preparation, execution, and post-processing of the load test. It also includes a discussion of the cost-savings (economic, environmental, and social) that are obtained through this procedure compared to a replacement of the super-structure.

In Chapter 10, Assessment of the deterioration of concrete structures using a finite element model, finite element (FE) modeling is used to assess the deterioration of...
concrete structures is discussed. In particular, focus is placed on reviewing the state of the art of FE model updating techniques. To illustrate the potential of the method, a case study is presented and discussed in detail.

Innovative materials for concrete repair and rehabilitation are the subject of Part II (Chapters 11—20).

Chapter 11, Geopolymer mortars based on different aluminosilicates, presents geopolymeric repair mortars based on metakaolin, fly ash and slag. This chapter also includes some comments about the EN 1504-3 requirements for the performance (including durability) and the safety of products and systems to be used for the structural and non-structural repair of concrete structures.

Chapter 12, Geopolymers mortars based on a low reactive clay, discloses results of an investigation concerning the development of geopolymeric repair mortars based on a low-reactive Tunisian clay. Geopolymeric mortars were studied for workability, compressive strength, adhesion, unrestrained shrinkage and modulus of elasticity. Several concrete beams, rehabilitated with a metallic grid and geopolymeric mortars were also tested for flexural strength.

Chapter 13, Assessment of corrosion protection methods for reinforced concrete, presents an evaluation of different prevention and control methods for the corrosion of reinforcing steel embedded in concrete after exposure to aggressive environments, including chlorides and/or carbonation. The methods include: the addition of permeation-reducing materials, the application of electrochemical methods, and the use of a geopolymer coating.

Chapter 14, Sulfoaluminate cement based concrete, concerns the synthesis of sulfoaluminate cement using primary and alternative raw materials, its hydration reaction with the presences of admixtures and OPC, its durability, and its usages for repairing in concrete infrastructures.

Chapter 15, Engineered cementitious composites based concrete, surveys Engineered Cementitious Composites (ECC) as new generation high-performance concrete repair and rehabilitation materials. Mechanical, dimensional stability, and durability properties of these High Performance Fiber Reinforced Cementitious Composites are discussed, along with a number of successful field applications.

Chapter 16, Self-healing concrete with encapsulated polyurethane, addresses the case of bacteria-based concrete. Production aspects of bacteria, suitable for concrete applications, are reviewed, including some cost-related comments. The cases of direct addition of bacteria to concrete and the application of bacteria for concrete surface protection are discussed in detail. Protection strategies, through encapsulation or immobilization of bacteria, are reviewed. Important data and discussion concerning the application of encapsulated bacteria for self-healing concrete are included.

Chapter 17, Concrete with super absorbent polymer, reviews self-healing concrete using encapsulated polyurethane. Its resulting crack closure efficiency, regain in impermeability, mechanical properties, and durability is demonstrated. The possible extension in service life which can be obtained through the use of this self-healing technique is described.
Chapter 18, Concrete with self-sensing properties, presents an overview of these properties and its effects on fresh and hardened concrete. It then discusses potential applications in concrete, including the use of SAP as an admixture for internal curing to mitigate autogenous shrinkage, improve freeze-thaw resistance, and induce self-sealing/healing of cracks. The focus is to review recent studies of SAP in concrete, identify gaps in knowledge and highlight future research needs.

Chapter 19, Bacteria based concrete, gives an overview on the current state of development of the technology of self-sensing concrete, also highlighting the most fruitful research, directions for the full development of its potential. Topics covered in the chapter include composition and processing of self-sensing concrete, strain sensing methods and models, main fields of applications, research trends and open problems.

Chapter 20, Bio based admixture with substances derived from bacteria for the durability of concrete, assesses the performance of bio-based admixture as corrosion inhibitor for steel bars used in concrete as reinforcement. Electrochemical methods, such as linear polarization and impedance spectrometry, were used to check the influence of the bioadmixture towards steel corrosion.

Finally, Part III presents Design, LCC, LCA and several case studies (Chapters 21—25).

Chapter 21, Eco-efficient design of concrete repair and rehabilitation, covers eco-efficient design of concrete repair and rehabilitation. A framework for eco-efficient design is presented and a case study concerning a concrete mix design for a reinforced concrete beam is included.

Chapter 22, Cost-effective design to address climate change impacts, poses the problem of adaptation for deteriorating RC structures, due to climate change actions. It describes a framework for evaluating the cost-effectiveness of adaptation measures that accounts for deterioration models, probabilistic methods, and cost-benefit analysis. The methodology is illustrated with an example focusing on cost-effective adaptation of existing RC structures placed in coastal French cities.

Chapter 23, Life cycle cost and performance analysis for repair of concrete tunnels, discusses concrete tunnel maintenance: from the tunnel structure, deteriorations and maintenance practice, to the eco-efficient maintenance. In order to realize the maximum utilization of the facility with the minimum LCC, a framework was proposed with the performance and LCC as the benchmarks for the decision-making, and was successfully applied to a tunnel.

Chapter 24, Life cycle analysis of strengthening concrete beams with FRP, analyses the implications, with respect to the environmental dimension of sustainable development, resulted from considering different carbon fiber reinforced polymers for strengthening reinforced concrete beams.

Chapter 25, Life cycle analysis of repair of concrete pavements, closes Part III with a chapter on the current state-of-practice in life-cycle cost analysis (LCCA) and life-cycle assessment (LCA) of concrete pavement as critical to developing eco-efficient concrete pavement repair solutions for overall sustainability.
References


Introduction


