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Joaquim A.O. Barros
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Recent Advances on Green Concrete for Structural Purposes

The Contribution of the EU-FP7 Project EnCoRe

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Preface

This book aims at summarising the results obtained in the Research Project entitled "Environmentally-friendly solutions for Concrete with Recycled and natural components" (EnCoRe, FP7-PEOPLE-IRSES-2011, Project ID: 295283), funded by the European Union as part of the 7th Framework Programme. The Project, whose activities have been developed during the three years 2012–2014, gathered three European Beneficiary Institutions (namely, *Università degli Studi di Salerno* and *Politecnico di Milano*, from Italy, and *Universidade do Minho*, from Portugal) and three non-European Partners (namely, *Universidad de Buenos Aires* and *Universidad Nacional de Tucuman*, from Argentina, and *Universidade do Rio de Janeiro*, from Brazil).

As stated by the title, EnCoRe was intended at investigating the physical and mechanical behaviour of cementitious composites made out of recycled and natural constituents. In fact, this is a subject of current relevance in both building technology and structural engineering, as a result of the growing interest to make the construction industry "greener". Specifically, the three following classes of materials have been considered:

1. Concrete with recycled aggregates and partial replacement of Ordinary Portland Cement (OPC);
2. Concrete reinforced with recycled fibers;
3. Cementitious composites internally reinforced with natural fibers or textiles.

However, this book is structured into two main parts. Part 1 covers the behaviour of a material belonging to the first one of the aforementioned classes and often referred to as Recycled Aggregate Concrete (RAC), as it is made with Recycled Concrete Aggregates (RCAs). Further insights are also reported on the effect of replacing OPC with Fly Ash (FA), a by-product of carbon-fed power plants, which is characterised by marked pozzolanic properties. Part 2 summarises the results obtained on cementitious composites internally reinforced with either recycled or natural fibers. Specifically, Recycled Steel Fibers (RSFs) obtained from post-consumed pneumatic tyres, and Natural Fibers (NFs) produced from tropical plants, such as sisal, are considered in this section.

The two main parts of this book consist of a number of *sections* treating the relevant knowledge derived from the research carried out as part of EnCoRe, which was also complemented with the available information in the performed literature review. The organization and contents of the sections aims to provide information from the technology up to the design. In fact, they summarise the empirical evidence about the physical and mechanical behaviour of the materials under consideration, and outline the theoretical models and the numerical procedures that can be formulated and implemented for simulating the behaviour of these materials. Moreover, a first attempt to propose a consistent conceptual formulation capable to make "predictable" their mechanical properties is also reported.

Although enhancing sustainability of cementitious composites is the fundamental motivation of this study, no consideration is reported within the book about the Life Cycle Assessment (LCA) of the materials addressed by the EnCoRe project. However, since the Project has contributed to an advance of knowledge on the mechanical behaviour of the aforementioned "environmentally-friendly" materials (and, hence, on their potential to be employed in field applications), its results can be used as input data by environmental scientists eventually interested in performing LCA on the materials investigated as part of the EnCoRe Project.

Finally, the book editors wish to acknowledge the tremendous contribution given by the members of the research groups belonging to the six Institutions that took part in EnCoRe: their names are listed at the beginning of each book section with the twofold aim to highlight the role played by the each researcher and the cooperation developed between the concerned research groups.

Guimarães, Portugal — Joaquim A.O. Barros
Milan, Italy — Liberato Ferrara
Salerno, Italy — Enzo Martinelli

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Part I
Recycled Aggregate Concrete

Chapter 1
State of Knowledge on Green Concrete with Recycled Aggregates and Cement Replacement

Enzo Martinelli, Eduardus A.B. Koenders and Marco Pepe

Abstract Since the construction industry is characterized by a huge demand for both energy and raw materials, it is fully concerned by the need for enhancing sustainability, which is certainly the main challenge for all industrial sectors in the twenty-first century. Therefore, several solutions are nowadays under investigation to reduce the environmental impact of concrete production. They often consist of partially replacing the ordinary concrete constituents with recycled ones, in view of the objective of reducing both the demand of raw materials and the amount of waste to be disposed in landfills. The most recent advances in this field are summarized in this chapter, which is intended at drawing the line of the current state of knowledge on "sustainable" structural concrete.

Concrete is the most widely used construction material and, hence, the reduction of the environmental impact induced by its production processes is a relevant and timely challenge for modern science and technology.

As a matter of fact, the production of concrete is characterised by a considerable demand for energy and raw materials and results in significant emission of Greenhouse Gases (GHG). Specifically, the cement production industry is deemed responsible for about 5% of the total CO_2 emissions, whereas the whole concrete production leads to almost double this share (Moya et al. 2010).

Moreover, the construction of new buildings, as well as the maintenance and/or demolition of existing ones, is responsible for the production of large amount of waste, commonly referred to as Construction & Demolition Waste (CDW), which generally require environment-sensitive and expensive disposal procedures (Moll et al. 2005).

Therefore, recycling these waste to replace part of ordinary aggregates (OA) is a straightforward and rational solution to produce more sustainable and

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environmentally-friendly concrete, also for structural applications (USDT 2004). Furthermore, replacing part of the Portland cement needed in ordinary concrete mixtures with alternative binders, often obtained by recycling industrial by-products, is a viable option for reducing the emissions of GHG due to the production of concrete (Lothenbach et al. 2011). These and other possibilities are currently under investigation for enhancing sustainability in the concrete industry by reducing the environmental impact due to producing and supplying the aforementioned ordinary constituents and the water always needed in concrete mixtures (Sandrolini and Franzoni 2001).

This chapter is intended at providing an overview of the current state of knowledge about the physical and mechanical properties of a wide class of materials, often referred to as "green concretes" (fib 2013).

First of all, Sect. 1.1 analyses the most promising solutions for producing and supplying alternative constituents whose use in concrete production can result in a significant reduction of the environmental impact. Specifically, this close examination is subdivided into three main parts dealing with recycled aggregates, alternative binders and further solutions for the other concrete constituents. The main physical properties, also connected to the most industrially feasible processing solutions, are examined in these subsections that are intended at describing the main differences between these "sustainable" concrete constituents and the ordinary ones, in terms of both physical and mechanical properties.

Although several options have been explored for producing concrete and other cementitious composites with recycled constituents, the following sections focus on the ones intended at obtaining structural concrete by employing Recycled Concrete Aggregates (RCAs), possibly in conjunction with industrial by-products, such as Fly-Ash (FA) or Silica Fume (SF). Therefore, Sect. 1.2 outlines the most recent findings about the fresh-state behaviour of concrete made with RCAs, generally referred to as Recycled Aggregate Concrete (RAC), and the influence of the possible use of the aforementioned mineral additions. Moreover, the current state of knowledge on the physical and mechanical properties of RAC and their correlation with the relevant engineering properties of the constituents is outlined. Unveiling these correlations is a key step for making predictable the resulting physical characteristics and mechanical properties of these "green" concretes. However, no general well-established theory has been formulated and validated so far. In this respect, the current codes and guidelines generally provide strict limitations on the use of recycled constituents: a wide overview of these codes and guidelines is proposed in Sect. 1.4.

Moreover, Sect. 1.5 proposes an overview of the main contributions about the environmental implications of both producing concrete with the aforementioned components and quantifying the possible beneficial effects on sustainability.

It is worth highlighting that the following sections focus on the most recent advances in this broad field of research and, hence, it refers to theoretical and experimental contribution appeared in the last decade in the international scientific literature. For a further discussion about the first studies on the mechanical characterisation of cementitious composites made out by replacing part of the ordinary constituents with recycled ones, the Reader may refer to well-established texts (Hansen and Narud 1983; Hendriks et al. 2005).

1.1 Sustainable Concrete Constituents

Sustainable concrete constituents can be obtained by recycling various classes of waste and by-products (Pacheco-Torgal et al. 2013). Since aggregates and binders are generally the main ingredients in any concrete mixtures, the following subsections only deal with the most recent advanced in classifying, producing, processing and employing these two main constituents for producing structural concrete. Although some studies address the effect of recycling water (CCAA 2007), this aspect is not covered in the following subsections.

It is worth highlighting that the definitions adopted hereinafter are inspired to the classical "terminology" adopted by Hansen (1986a, b): therefore, the notation adopted by other authors is sometimes modified for being consistent with the aforementioned work.

1.1.1 Recycled Aggregates

Recycled aggregates can be produced by using various types of waste, often deriving from Construction and Demolition Waste (CDW), but also obtained through other types of waste that are not strictly connected with the construction section and the concrete production (Kuosa 2012). Other sources of waste, not only belonging to the class of CDW, that may be recycled and employed as aggregate in concrete are listed and discussed into details by de Brito and Saikia (2013). Further classifications are available both in national pre-standard regulation documents (Kreijger 1981) and in the international scientific literature (Butler et al. 2014). Other proposals deals with the use of such aggregates for specific purposes (Zhu et al. 2011; Tebaldi et al. 2012). However, the present discussion is restricted to CDW and the expression "Recycled Aggregates" (RAs) identifies aggregates produced by crushing and processing any kinds of CDW. Specifically, Recycled Concrete Aggregates (RCAs) are those obtained by selecting, crushing and processing concrete members coming from different sources, such as the demolition of existing buildings or the recovery of residuals in pre-cast concrete factories (Pedro et al. 2014) and unused concrete returned to plant (Ferrari et al. 2014).

Although RCAs are the most relevant option for the subject under discussion in this book, RAs can be further classified by considering their original materials and, hence, the following main classes can be recognised within CDW:

- Recycled Masonry Aggregates (RMAs), obtained by crushing masonry bricks (Corinaldesi 2012);

- Recycled Ceramic Aggregates (RCerAs), obtained by crushing waste ceramic tiles and sanitary ware (Alves et al. 2014);
- Recycled Glass Aggregates (RGAs), mainly intended at replacing the fine fraction of natural concrete aggregates (Adaway and Wang 2015; Mardani-Aghabaglou et al. 2015).

Moreover, RAs derived by industrial activities that are connected with construction and demolition (such as the extraction and transformation of marble stones) are also considered in the scientific literature as a viable source of recycled aggregate for concrete (Corinaldesi et al. 2010).

However, demolition and processing generally imply that the various types of aggregates get mixed and, hence, some classifications adopted within the scientific literature take into account the possibility that recycled aggregates do not belong to a unique waste source (Yang et al. 2011). To this extent, the following classification was recently proposed (Agrela et al. 2011):

- Concrete Recycled Aggregate (CRAs) in which concrete content is at least 90% (in weight);
- Mixed Recycled Aggregate (MixRAs) in which the ceramic content ranges between 10 and 30%;
- Ceramic Recycled Aggregate (CerRAs), containing more than 30% of ceramic particles.

Since concrete and ceramic (sometimes using the latter term in a broader sense including also masonry) are the main sources of waste produced in construction and demolition of buildings, a further classification criterion intended at a visual selection of these two main waste streams can be based on their colors and, hence, defines the two following "fraction" (Toledo Filho et al. 2013):

- the *grey* fraction, consisting of particles mainly made of structural concrete (and, in a minor portion, mortar) debris
- the *red* fraction, including clay bricks and ceramic-based (i.e. tiles) materials.

Classifications based on the original source of RAs are certainly useful, as they can drive the selection and separation processes, either during demolition or in dedicated recycling plants (Mas et al. 2012). However, a *performance related approach* (WRAP 2007), intended at classifying recycled aggregates in terms of their relevant engineering properties, would be more useful for the design of concrete mixtures employing these sustainable constituents. Experimental evidences highlighted that the actual content of *red* particles controls the main engineering properties of aggregate (Agrela et al. 2011). However, the mere classification by origin does not lead to CDW aggregates with homogeneous properties: as a matter of fact, water absorption measured in concrete aggregates, albeit collected in the same geographic area, can be extremely variable (Angulo et al. 2010).

Therefore, a more accurate performance-based classification, based on the tests usually carried out for concrete aggregates (CEN 2013) and intended at determining the main geometric (such as grain size distribution and shape parameters), physical (such as density and water absorption) and chemical properties (such as total sulfur, acid-soluble sulfate and chlorides contents) is needed (McNeil and Kang 2013; Rodríguez-Robles et al. 2014). For instance, the sink–float technique is a reasonably feasible tool for separating CDW in different density classes (Angulo et al. 2010).

Based on the results of these tests, a close correlation between water absorption (WA) and oven-dried density (ODD) was recently unveiled by analyzing the data regarding 589 aggregates of different types, sizes, origins, and sourced drawn from 116 publications. The statistical processing of these data and, particularly, a regression analysis carried on the two aforementioned quantities led to the following polynomial relationship (Silva et al. 2014):

$$\mathrm{WA} = A_3 \cdot \mathrm{ODD}^3 + A_2 \cdot \mathrm{ODD}^2 + A_1 \cdot \mathrm{ODD} + \mathrm{A}_0 \tag{1.1}$$

where WA is expressed in percentage and ODD in kg/m^3, and the constants assume the following values: $A_3 = 2.9373\ 10^{-9}$, $A_2 = -9.4014\ 10^{-6}$, $A_1 = 1.8977\ 10^{-2}$ and $A_0 = 65.745$. Silva et al. (2014) also reported further statistical information intended at describing the distribution of the experimental results with respect to the relationship (1.1); particularly, a coefficient of determination $R^2 = 0.878$ was estimated.

The correlation described by relationship (1.1) is the basis for a classification proposed by the same Authors for CDW waste in view of their use as RCAs (Silva et al. 2014): four classes, denoted with A, B, C and D, ranging from the better to the worse one, were defined.

A similar idea is presented herein, around the definition of a Quality Index QI of RCAs:

$$\mathrm{QI}^{\mathrm{RCA}} = \frac{\mathrm{WA}^{\mathrm{OA}}}{\mathrm{WA}^{\mathrm{RCA}}} \tag{1.2}$$

where $\mathrm{WA}^{\mathrm{OA}}$ is the water absorption of ordinary aggregate that is going to be replaced, and $\mathrm{WA}^{\mathrm{RCA}}$ is the one of the recycled aggregate under consideration. In principle, the QI should be defined for each relevant size range considered in the mixture.

Both criteria and any other classification approach based on either of the aforementioned quantities is based on the physical observation that, especially in RCA (Pepe et al. 2014a, b), but also in other types of RAs (Corinaldesi and Moriconi 2009a; García-González et al. 2014), porosity is mainly related to attached mortar (AM). Since AM is one of the key parameters affecting the relevant properties of concrete at both fresh and hardened states (Duan and Poon, 2014), it should be carefully considered in rational mix-design rules for RAC (Fathifazl et al. 2010). As a matter of fact, these quantities can also be controlled by means of various techniques intended at “cleaning” the outer part of AM and reducing the particle of crushed concrete as close as desired to the original properties of the original OA. In fact, the “autogenous cleaning” process, based on treating crushed concrete particles in a rotating mill for a certain time, is a viable solution for reducing the amount of AM and, hence, controlling all the related engineering properties of RCAs, such as density, water absorption and porosity (Pepe et al. 2014b). As it can be expected, the processing procedure plays a key role on the resulting quality of RCAs and, hence, of RAC. In fact, experimental results demonstrated that RCAs processed by coupling a primary plus secondary crushing (PSC), using a jaw crusher followed by a hammer mill, performed significantly better than the case in which a simple primary crushing process is executed (Pedro et al. 2014).

The results show that the PSC process leads to higher performance, especially in terms of durability. The experimental evidence highlights that higher contents of AM with scarce presence of natural aggregates characterizes the smaller size fractions of RAC (Evangelista et al. 2015). This is the reason why, as it will be reported in Chap. 2, the use of RCA for replacing the fine fraction of is not generally allowed for producing structural concrete (NTC 2008). However, several studies have demonstrated that the weaknesses induced by the higher porosity of RCA can be somehow balanced by means of mineral additions often derived by recycling environmentally harmful industrial by-products, such as FA and SF. Particularly, the former, when employed in partial replacement of the finer fraction of aggregates, has been shown to be able to enhance workability and strength of RAC (Kou et al. 2008; Lima et al. 2013). Moreover, the addition of fly ash has been also very effective in reducing carbonation and chloride ion penetration depths in concrete, even in RAC (Corinaldesi and Moriconi 2009b). The aforementioned by-products are also characterised by pozzolanic properties (Wang et al. 2013; Dilbas et al. 2014) and, hence, they can be employed in partial substitution of Portland cement, in view of an even more sustainable structural concrete.

Finally, RCA have been proved to be suited also for producing High-Performance concrete: however, the quality (i.e. the mechanical properties) of the original concrete plays a decisive role in limiting the maximum strength of RAC (Gonzalez and Etxeberria 2014).

1.1.2 Alternative Binders

Portland Cement (PC) is an essential constituent of concrete as it has been produced and utilized so far. As already said, the production of PC is deemed responsible for a significant share of the global GHG emissions. Therefore, reducing the amount of PC needed for producing structural concrete of a given *quality* (in terms of resulting physical and mechanical properties) would result in a straightforward reduction in the environmental impact of the concrete industry and the construction sector as a whole.

The hydration reaction of PC developing in concrete mixtures during the phase generally referred to as “setting” and “hardening” are characterized by a number of coupled chemical processes whose kinetics is determined by both the nature of the process and the state of the system at that instant. A macroscopic interpretation of these reactions based upon combining two well-established physical tools, such as the heat transfer theory and the Arrhenius principle, is capable of reproducing the influence of thermal boundary conditions on the resulting rate of hydration and the time development of the reaction heat and temperature throughout concrete (Azenha 2009; Ventura-Gouveia 2011; Martinelli et al. 2013).

However, a more fundamental analysis of the hydration reaction highlights six main chemical processes (generally referred to as: *dissolution/dissociation, diffusion, growth, nucleation, complexation, adsorption*) that may develop either in series or parallel, the latter case resulting in a further complication of this complex chemical system (Bullard et al. 2011).

The growing interest for developing more sustainable concretes and cementitious composite materials is leading to considering more and more the possible employment of secondary mineral additions, generally referred to as *supplementary cementitious materials* (SCMs, Lothenbach et al. 2011) and often originating as by-products of other industrial activities. Therefore, a more complete knowledge of the fundamental mechanisms of hydration is needed to provide a rational basis for selecting the most effective constituents and designing more sustainable concrete mixtures. Furthermore, PC is not the ideal binder for all construction applications, as it suffers from durability problems in particularly aggressive environments. Several alternative binders have been available for almost as long as Portland cement but, despite this, they have not been yet extensively used (Lollini et al. 2014).

The most promising alternative binders currently available can be classified as follows (Juenger et al. 2011):

- *Calcium aluminate cements* featuring rapid strength development and good durability in high sulfate environments;
- *Calcium sulfoaluminate cements* characterized by low CO_2 emissions and energy demand, but with several unknown aspects on the time development of mechanical properties and long-term durability;
- *Alkali-activated binders* often obtained by recycling from waste materials and industrial by-product and, hence, exposed to the natural variability about physical compositions and chemical properties of these waste and by-products;
- *Supersulfated cements* almost entirely made from waste materials, coupled with low heat production and good durability in aggressive environments such as seawater.

Based on the above short descriptions, it is clear that the last two classes have potential to be employed in "green concrete" for reducing the demand of PC. As regards the alkali-activated binders (Pacheco-Torgal et al. 2008), the following five categories can be introduced and considered in the following classification (Shi et al. 2011):

- *Alkali-activated slag-based cements*, including blast furnace slag cement, phosphorus slag cement, blast furnace slag-fly ash cement, blast furnace slag-steel slag cement, blast furnace slag-MgO cement, blast furnace slag-based multiple component cement

- *Alkali-activated pozzolan cements*, including fly ash cement, natural pozzolan cement, metakaolin cement, soda lime glass cement;
- *Alkali-activated lime-pozzolan/slag cements*, lime–natural pozzolan cement, lime–fly ash cement, lime–metakaolin cement, lime–blast furnace slag cement;
- *Alkali-activated calcium aluminate blended cement*, including combinations of calcium aluminate cement (CAC) with metakaolin, pozzolan and fly-ash;
- *Alkali-activated Portland blended cement (hybrid cements*), including Portland blast furnace slag cement, Portland phosphorus slag cement, Portland Fly ash cement, Portland blast furnace slag–steel slag cement, Portland blast furnace slag–fly ash cement, multiple components blended cements.

The use of Fly Ash and Silica Fume in partial replacement of cement has been also employed in junction with RCA (Corinaldesi and Moriconi 2009b; Mahmoud et al. 2013; Lima et al., 2013).

More recent solutions for a partial replacement of cement in concrete were developed by considering the ash obtained by burning municipal solid waste of agricultural waste. Three relevant examples of these emerging supplemental cementing materials are reported below:

- *Rice-Husk Ash* (*RHA*);
- *Sugar Cane Bagasse* (*SCB*) *ash*;
- *Municipal Solid Waste Incinerator* (*MSWI*) *ash.*

Rice husk is an agricultural residue that accounts for 20% of the 649.7 million tons of rice produced annually worldwide. The chemical composition of rice husk is found to vary from one sample to another due to the differences in the type of paddy, crop year, climate and geographical conditions. Burning the husk under controlled temperature below 800 °C can produce ash with silica mainly in amorphous form Ghassan and Hilmi (2010). The performance of RHA as a supplemental cementing materials was even investigated in Ultra-High Performance Concrete (UHPC) and the obtained results highlighted that RHA acts both as highly pozzolanic admixture and internal curing agent in UHPC (Van et al. 2014).

SCB ash is a by-product of the sugar/ethanol agro-industry abundantly available in some regions of the world and has cementitious properties indicating that it can be used together with cement (Fairbairn et al. 2010).

MSWI ashes have several applications. As regards the applications of relevance in cement and concrete industry, on the one hand, the addition of MSWI ash for clinker production has been demonstrated to shorten the setting time and decrease workability. On the other hand, experimental results demonstrate that addition of up to 50% treated MSWI fly ash does not significantly affect the mechanical properties (Lam et al. 2010).

Finally, nanotechnology offers further options for reducing the amount of cement needed in concrete. Specifically, incorporating colloidal Nano-Silica in concrete with 100% coarse RCAs led to similar results, in terms of mechanical properties, with respect to a reference concrete mixture (Mukharjee and Barai 2015).

1.2 Fresh-State Behaviour

The peculiar features characterising RCAs have a significant influence in affecting the properties of concrete at the fresh-state. Particularly, they generally affect workability due to the two main reasons explained below:

- the higher porosity and water absorption capacity of RCAs have an interaction on the water actually available in the mixture: initially dry RCAs result in a reduction of the free water and, hence, a reduction of workability, whereas, part of the water absorbed in initially saturated ones can have the opposite effect (Pepe et al. 2014a);
- the higher irregularity and roughness of RCA particles with respect to ordinary aggregates generally leads to reduced workability (Safiuddin et al. 2011).

On the contrary, the addition of FA to RAC mixtures generally enhances workability: this is mainly due to the higher regularity and fineness of FA particles, which contribute to reducing friction interactions among aggregates in both normal (Lima et al. 2013) and self-compacting (Revathi et al. 2013) RAC.

Although the slump test (CEN 2009) is the most common methodology for quantifying workability in fresh concrete mixture, a systematic investigation carried out on concrete mixtures characterised by variable aggregate replacement ratio and water compensation rate demonstrated that the VeBe time and flow table tests are more suitable to determine workability of RAC. In fact, these testing techniques result are more capable to detecting the influence of relevant quantities, such as free water content and aggregates' shape (Leite et al. 2013). As a general observation, as it is easy to expect that, by increasing the water compensation rate results in enhancing workability (as a result of the well-known Lyse's rule) and reducing compressive strength at the hardened state (as a result of the well-known Abrams' law).

Therefore, chemical admixtures are required to guarantee the target workability without inducing detrimental effects on the resulting mechanical properties of RAC. Particularly, a new generation of superplasticizers containing some copolymer polycarboxylate makes it possible to significantly improve the fluidity of the RAC (Braymand et al. 2015). To a certain extent this superplasticizers can also compensate the detrimental effect induced by replacing the fine fraction of aggregate with recycled sand (Pereira et al. 2012).

An alternative option, intended at reducing the interaction of RCAs with free water, is based on tailored polymer-based treatments which consist in soaking these aggregates in polymer solutions and developing a water-repellent film on the aggregate outer surface. A recent study compared the effect of various polymers and variable concentrations of the aforementioned solutions on both the fresh and hardened state properties of RAC (Spaeth and Tegguer 2013).

Finally, due to the same reasons affecting workability, the presence of RCA has been proved to play a role in the initiation and development of the hydration reaction of concrete at early age: the aggregate replacement ratio modifies the reaction kinetics (Koenders et al. 2014) and the initial moisture condition of aggregates modifies the initial rate of reaction and the time development of cement hydration (Pepe et al. 2014a).

1.3 Hardened-State Behaviour

The properties of aggregates play a significant role also on the resulting behaviour of RAC at the hardened state, both in terms of mechanical response and physical durability-related parameters.

The present review of the most recent advances on this topic focuses on RAC made from RCAs, as it is proved to be the best suited option for producing “green” structural concretes. However, it is worth mentioning that studies on the mechanical characterisation of concrete with coarse RMAs or MixRAs (see Sect. 1.1) are available in the literature (Gomes and de Brito 2009). They demonstrate that limited replacement of natural aggregates with the aforementioned mixed recycled ones (lower than 25% in weight) result in concrete characterised by sufficient strength and durability for housing construction and almost the same physical properties with respect to the reference mixtures (Medina et al. 2014). Moreover, studies on the use of RGAs are also available: they are often intended at investigating the conditions of occurrence and the solutions for suppressing the Alkali-Silica Reaction (ASR) which can be harmful for the material durability (Rajabipour et al. 2010). The resulting behaviour of RAC made from mixed glass/concrete RAs has been also investigated for understanding the concurrent influence of the lighter glass particles and the more porous crushed concrete ones (Mardani-Aghabaglou et al. 2015). Furthermore, although the focus of the present review is on RAC for structural purposes, RCA seems particularly suited for some specific non structural applications, such as the production of pervious concrete (Chen et al. 2012; Güneyisi et al. 2016), as they are mainly made of coarse particle and should guarantee a significant water porosity (Sriravindrarajah et al. 2012). In fact, replacing the fine fraction of aggregates with fine RCA results in several detrimental effects on the resulting mechanical performance of RAC, among which a significant increase in shrinkage and creep deformation (Cartuxo et al. 2015).

Since the compressive strength f_c (generally determined after 28 days of curing) is the main design parameter for structural concrete, several studies on RAC focus on determining the role of RCA on the resulting value of this property. Although these are often limited to an empirical observations of the role of RCA on f_c, scrutinising the cement reactions developing in RAC unveils the fundamental influences of the main engineering parameters of both aggregates (i.e. either open porosity or water absorption capacity, along with their initial moisture condition at mixing) and mixtures (i.e. the water/cement ratio) on the resulting hydration kinetics (Koenders et al. 2014). However, it was demonstrated that RAC is affected by curing conditions (either laboratory conditions, external environment or wet chamber) roughly in the same way as ordinary concrete (Fonseca et al. 2011).

Between the mere empirical observation and these fundamental modelling approach, various quantitative relationships have been recently proposed for expressing the correlation between f_c depending on the main parameters describing the mix composition. These relationship are often formulated in terms of the $f_{c,RAC}/f_{c,RC}$ ratio between the compressive $f_{c,RAC}$ of RAC and the one, denoted $f_{c,RC}$, of the reference concrete (RC) mixture made with only ordinary aggregates and the same size grading of RAC (de Brito and Alves 2010):

$$\frac{f_{c,RAC}}{f_{c,RC}} = 1 - 2.619 \cdot \left(1 - \frac{D_{RAC}}{D_{RC}}\right) \quad (1.3)$$

where D_{RAC} and D_{RC} denote the *weighted density* of RAC and RC, respectively, determined across the various size fraction of aggregates included in the concrete mixtures under consideration. The relationship (1.3), determined on seven different series of experimental tests (mainly carried out on mixtures of RCAs) was calibrated for weighted density ratios ranging between 0 and 0.10 and exhibited a reasonably good correlation with the aforementioned experimental results (expressed by a coefficient of determination $R^2 = 0.7615$). The same authors (de Brito and Alves 2010) proposed similar relationships intended at expressing the correlation between the same weighted density ratio and other concrete properties, such as compressive strength at 7 days, splitting and flexural tensile strength, modulus of elasticity, abrasion resistance, shrinkage, water absorption, carbonation penetration and chloride penetration: the analytical expressions of these relationships are omitted herein and the interested Reader can refer to the cited paper for further details.

The knowledge achieved so far about the influence of RCAs on the resulting strength of RAC led to the formulation of generalised mix-design rules for the latter (Fathifazl et al. 2009; Yehia et al. 2015): a physically-based conceptual proposal based on the findings of a recent Ph.D. thesis (Pepe 2015) will be presented in Chap. 6. The structural scale response of RAC was investigated under both permanent and variable loads. On the one hand, the results obtained on RAC with 100% of coarse RCAs reveal that the ratio between strength determined at low loading rate and the standard one in compression and in tension is similar for RAC and ordinary concrete (González-Fonteboa et al. 2012). On the other hand, beam-to-column joints made of RAC with 30% limited replacement ratio (30% of the coarse aggregates) and subjected to cyclic-actions highlighted the suitability of using RAC in seismic zones (Corinaldesi et al. 2011).

Moreover, an empirical correlation was proposed for expressing the time evolution of strength (Malesev et al. 2010)

$$f_c(t) = \frac{a \cdot t}{t + b}, \quad (1.4)$$

where a and b are two constants whose values can be derived through best-fitting of the available experimental result: as it is clear, the parameter a represents the asymptotic value $f_{c,\infty}$ of f_c, whereas b (dimensionally a time quantity) controls the initial rate of growth of compressive strength. The relationship (1.4) will be considered and calibrated in the following Chap. 3 for the concrete mixtures reported therein.

Due to the peculiar properties of RAC and their interaction with the other mixture constituents, the resulting correlation between the compressive strength f_c and the other mechanical parameters cannot generally be expressed by means of the same analytical expressions adopted in Codes (CEN 2005) and Guidelines (fib 2013) for ordinary structural concrete. As regards the Young's Modulus E_c, the following correlation between its mean value and the cubic compressive strength of concrete $f_{c,cube}$ proposed (Corinaldesi 2010):

$$E_{cm} = 18800 \cdot \sqrt[3]{\frac{0.83 \cdot f_{c,cube}}{10}}. \tag{1.5}$$

This relationship was calibrated on the results obtained from RAC specimens with five different water/cement ratios (ranging from 0.40 to 0.60) and replacement ratio of 30% of the coarse aggregates. The experimental results highlighted that compressive strength was almost unaffected by RCAs, whereas RAC exhibited lower static elastic modulus: this reduction was around 10% and justifies the reduction of the coefficient adopted in Eq. (1.5) with respect to the one currently in use for ordinary concrete (CEN 2005; fib 2013).

Moreover, analytical relationships were also proposed for generalising the Sargin curve, adopted by the aforementioned Codes and Guidelines, to take into account the increase in axial deformability observed in RAC. Specifically, three coefficients α_c^{rec}, β_{cu}^{rec} and φ_{cm}^{rec} were calibrated by González-Fonteboa et al. (2011) for modifying the values of ε_{c2}, ε_{cu} and E_{cm} defining the stress-strain curve for ordinary structural concrete (CEN 2005; fib 2013):

$$\alpha_c^{rec} = 0.0021 \cdot RR_{CRCA} + 1, \tag{1.6}$$

$$\beta_c^{rec} = 0.0022 \cdot RR_{CRCA} + 1, \tag{1.7}$$

$$\varphi_{cm}^{rec} = -0.0020 \cdot RR_{CRCA} + 1, \tag{1.8}$$

where RR_{CRCA} is the percentage of coarse RCA employed in the concrete mixture. The relationship (1.8) confirms that the reduction in E_{cm} expected for RAC with replacement ratio lower than 30% foresees a reduction in strength lower than 10%, as already found by the aforementioned Author (Corinaldesi 2010). Moreover, similar conclusions can be achieved by means of alternative analytical expressions proposed for the stress-strain curve of RAC under uniaxial compression (Wardeh et al. 2015). A complete constitutive formulation capable of simulating the response and predicting the failure mode of members made of RAC and subjected to tri-axial stress states (Folino and Xargay 2014) would also lead to the same conclusions. Further mechanical properties of interest for reinforced concrete structures, such as bond between RAC and deformed steel rebars, were recently investigated for understanding the influence of RCA and the bond-slip relationships generally adopted for ordinary concrete were recalibrated for RAC characterised by either normal (Prince and Singh 2014a) or high strength (Prince and Singh 2014b). Moreover, the widely adopted non-destructive testing techniques, such as those based on ultrasonic velocity (Rao et al. 2011) and acoustic emissions (Kencanawati et al. 2013), were recalibrated for RAC.

The mechanical response under sustained loads and, particularly, the development of creep and shrinkage phenomena are other features of relevance in RAC for structural purposes. Experimental observations confirm that the evolution of these phenomena in RAC is fairly similar to the one of ordinary structural concrete, although a certain influence of the aggregate replacement ratio can be detected. An experimental study available in the literature shows creep increase of around 50% and shrinkage increase of about 70% in RAC specimens with 100% replacement of coarse aggregate tested in uniaxial compression (Domingo et al. 2010). However, the same study highlighted much lower differences for RAC specimens with lower replacement ratio, the one made from 20% of recycled aggregate being almost unaffected by the effect of RCA on creep and shrinkage. For this reason, it is generally accepted that no formal changes are needed to the general models available in Codes and Guidelines for ordinary concrete. Fathifazl and Razaqpur (2013) suggested only to introduce a new coefficient for increasing the basic predictions based on those models. As regards the response under tensile stresses, a uniaxial restrained shrinkage cracking test was executed to investigate the tensile creep properties caused by the restraint of drying shrinkage of RAC: the results highlighted that the tensile creep of RAC caused by the restraint of shrinkage was about 20–30% higher than that of the corresponding RC (Seo and Lee 2015).

Finally, durability is the other main aspect of concern in RAC. Correlation between compressive strength and durability-related properties, mainly controlling carbonation and chloride ingress, are available in the literature. Specifically, the following relationship between chloride migration coefficient D_{nssm} and compressive strength f_c was recently proposed (Silva et al., 2015a, b):

$$D_{nssm} = 47.618 \cdot e^{-0.024 \cdot f_c}. \tag{1.9}$$

Besides the common belief, the presence of fine recycled aggregate (FRA), that is technically feasible for low replacement ratios (e.g. <30%), does not lead to any reduction in durability (Evangelista and de Brito 2010). Conversely, the possible “contamination” of RAC due to the presence of chlorides or sulphates plays a significant role on mechanical and durability-related properties of RAC (Debieb et al. 2010).

All the aspects mentioned in this section will be further developed in the following sections of this chapter. For other issues, not addressed in this book, the Reader may refer to Behera et al. (2014).

1.4 Codes and Guidelines

Several codes, regulations and guidelines dealing with the use of recycled aggregates in concrete are available worldwide. Particularly, the most comprehensive documents concern countries, such as Hong Kong and North European countries, where waste disposal represents a crucial problem due to morphological and environmental conditions, or industrial countries, which have promoted a new urban development process (e.g. Germany during the last few decades). This section proposes an overview of the most significant documents that are currently in force in various regions of the world.

1.4.1 Europe

RILEM, among the first concerned Institutions, proposed some specifications for concrete with recycled coarse aggregates, while the use of recycled sand was not recommended (RILEM 1994). Therefore, these recommendations deal with Recycled Coarse Aggregate Concrete (RCAC) and suggest a classification of this material according to material composition: RCAC Type I is mainly constituted by crushed brick, RCAC Type II is made of crushed concrete, while RCAC Type III is recycled material from concrete and brick mixture containing up to 50% brick. Focusing the attention on RCAC Type II, it is allowed a total replacement of natural coarse aggregates with recycled ones in concretes up to class C50/60.

Similarly, the structural code currently in force in Italy (NTC 2008) only allows the use of recycled aggregates for replacing the coarse fraction of aggregates in new concrete production. A total replacement of natural aggregates, by recycled ones made of CDW, it is allowed only for concrete produced for non-structural applications. In the case of structural concrete, the maximum allowed percentage of RCAs is strongly limited for the usual compressive strength targets related to structural elements.

In Germany, recycled aggregates are classified into four types, depending on the material composition (DIN 4226-100 2002). Particularly, Type 1 and Type 2 derive both from demolition of concrete structures, but the minimum content of concrete plus natural aggregate should be at least 90 and 70% by mass, respectively; the other part may consist of clinker and calcium silicate bricks. Type 3 shall contain more than 80% of dense bricks, and it generally is obtained from pure brick masonry demolition. Finally, Type 4 is a mixture of all mineral building materials without strict specification of the constituents. In terms of applications and mechanical requirements, the best reference is the “Guideline of the German Committee for Reinforced Concrete (DAfStb 1998)”. This document specifies that only aggregates with equivalent size bigger than 2 mm belonging to Type 1 or Type 2 can be used in producing structural concrete; moreover, it proposes correlations between replacement percentage and mechanical performance of recycled aggregate concrete.

In the United Kingdom, the BS 8500-2 (2006) provides general requirements for coarse recycled aggregate. In accordance with the use of recycled concrete aggregate in new concrete production, a maximum of 20% replacement of coarse aggregate is allowed and the corresponding compressive strength is limited between 20 and 40 MPa. Moreover, it is specified that RAC can be used for unreinforced members, internal elements or external elements not exposed to chlorides or subject to de-icing salts. RAC also cannot be used in foundations or paving elements. Finally, it is useful to note that no provisions are given in BS 8500-2 for the use of fine recycled aggregates, but their use is not it precluded in principle.

The Spanish Code on Structural Concrete EHE-08 (2008), in annex 15 "*Recommendations for using recycled concrete*", specifies that the use of coarse recycled concrete aggregates is allowed in structural concrete for replacing up to 20% (by weight) of the total amount of coarse aggregates. However, this is only allowed for concrete with cylindrical compressive strength up to 40 MPa and the recycled aggregates should be characterised by a water absorption capacity lower than 7%.

The same limitation in terms of replacement ratio is provided by the French standard NF EN 206-1/CN (2012) for concrete classes up to C35/45 to be employed in the exposure classes XC1, XC2, XC3, XC4 or XF1, provided that the origin of demolished/deconstructed concrete is traceable.

1.4.2 United States, Hong Kong and Australia

The American Concrete Institute (ACI) highlights that possible sources of RAs can be identified in concrete pavements, structures, sidewalks, curbs and gutters that when are removed can be used in concrete production. Particularly, ACI E-701 (2007) specifies that new concrete mixtures can contain both fine and coarse recycled aggregate. Although up to 100% of the coarse aggregates can be made of recycled materials, the percentage of fine aggregate replacement is usually limited to 10–20%.

The Buildings Department of Hong Kong proposed one of the most detailed Guidelines about the use of recycled concrete aggregates (HKBD 2009). These Technical Guidelines specify that concrete with 100% of recycled coarse aggregates shall only be used for non-structural works. Both 100 and 20% recycled coarse aggregates analysed in these guidelines, shall be produced by crushing old concrete.

The Cement Concrete & Aggregates Australia (CCAA), that is the main national body in Australia (representing the interests of six billion dollar a year heavy construction materials industry), recently published an interesting document reporting the current knowledge about the use of recycled aggregates in new concrete production (CCAA 2008). The Commonwealth Scientific and Industrial Research Organisation (CSIRO 2002) and the Standards of the Concrete Institute of Australia are the most important references for this document. Five types of recycled aggregates are identified and classified: Recycled Concrete Aggregate

(RCA), Recycled Concrete and Masonry (RCM), Reclaimed Aggregate (RA), Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Aggregate (RAA). As CSIRO reported, Class 1A RCA (which is a good quality RCA with no more than 0.5% brick content) has the potential for being used in a wide range of applications. Applications include partial replacement of ordinary material in concrete production for non-structural components, such as kerbs and gutters. Although CSIRO (2002) emphasizes that the current field experience with the use of RCAs for structural applications is scarce, it contributes to clarify this matter and defines two different grades of RAC both made by using Class 1A RCAs:

- Grade 1 RAC, characterized by a maximum 30% replacement ratio with Class 1A coarse RCAs, has a maximum specified compressive strength limit of 40 MPa;
- Grade 2 RAC, made of up to 100% Class 1A coarse RCAs recycled, has a maximum specified compressive strength limit of 25 MPa.

1.4.3 Some Remarks About Existing Regulations and Standards

As the aforementioned recommendations show, the use of RCAs is intended mostly to replace the coarse fraction of ordinary aggregates. In fact, recycled fine aggregate from concrete exhibit deleterious characteristics that might affect performance and workability of recycled concrete, especially if the concrete mixture is not accurately designed.

The requirements that aggregate shall meet in order to be used as RCA, seem to be almost the same for the documents proposed from different institutions: they are outlined in Table 1.1. Although it is required that RCAs mainly derive from demolished concrete, a certain limited content of other “alien” materials, such as metals, plastics, clay lumps and glass, is allowed. In this respect, only ACI 555R-01 (2001), among the current regulations, provides clear indications about a selective process of demolition intended at safeguarding the “purity” of RCAs. Conversely, the processing procedure implemented for producing recycled aggregates, is generally designed by operator companies, according to their specific practices.

A total replacement of coarse natural aggregates is allowed only for non-structural concrete, due to the decrease of compressive strength that generally occurs considering the recycled material source.

Moreover, the use of recycled coarse concrete aggregate is still limited in structural applications, as several international standards define an upper limit between 20 and 30% for their replacement ratio (in volume). Table 1.2 summarizes the main requirements and limitations provided by the regulations and guidelines considered herein.

Table 1.1 Recycled concrete aggregate requirements: synoptic overview

Code/guideline	Material source	Maximum content of fine (%)	Maximum content of "alien" materials
Italian Ministry of Infrastructure and Transportation (NTC 2008)	Building demolition (for non structural concrete) and concrete demolition (for structural concrete)	–	–
RILEM (1994)	–	5	1%
DAfStB (1998)	Demolished concrete structures	–	$\leq$0.2% (Type 1)
			$\leq$0.5% (Type 2)
British Standard Institution (BS 8500-2 2006)	Crushing hard concrete	5	1%
Building Department Hong Kong Government (HKBD 2009)	Crushing old concrete	4	1%
American Concrete Institute (ACI E-701 2007)	Removed pavements, structures, sidewalks, curbs, and gutter	–	2 kg/m^3
Cement Concrete & Aggregates Australia (CCAA 2008)	Demolition waste of at least 95% concrete	–	–

Note Metals, plastics, clay lumps and glass are considered as "alien" materials

Finally, selective demolition is generally needed in order to obtain materials that may be easily turned into RAC with limited need for further screening processes and decontamination procedures (HKBD 2004).

1.5 Insights into Concrete Sustainability

According to its original and most cited definition, "Sustainable development" should "meet the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). Therefore, no further speculation, that would be out of the scope of this work, is actually needed for understanding that the construction industry is fully concerned by the challenge of making its processes "sustainable". In fact, the building construction sector and the production of cement and concrete is responsible for a significant share of the global emissions and raw material demand (van den Heede and De Belie 2012). Particularly, 40% of anthropogenic GHG global emissions and 40% of raw materials are attributed to building construction sector, whereas the global annual production of concrete is going to approach 25 gigatonnes, namely 3.8 t per person (Gursel et al. 2014). Moreover, the production of CDW requires more and more

Table 1.2 Main characteristics of recycled concrete: synoptic overview

Country (guideline)	Application	Replaceable aggregate fraction	Maximum replacement percentage (%)	Maximum cylindrical compressive strength (28 days) (MPa)
Italy (NTC 2008)	Non-structural	Coarse	100	8
	Structural	Coarse	30	30
			60	20
RILEM (1994)	Not specified	Coarse	100	50
Germany (DAfStB 1998)	Structural	Coarse	35	25
			25	35
UK (BS 8500-2 2006)	Not specified	Coarse	20	40
Spain (EHE-08 2008)	Structural	Coarse	20	40
France (NF EN 206-1/CN 2012)	Structural	Coarse	20	35
Hong Kong (HKBD 2009)	Non-structural	Coarse	100	20
	Structural	Coarse	20	30
USA (ACI E-701 2007)	Not specified	Coarse fine	100	Not specified
			20	
Australia (CCAA 2008)	Grade 2 concrete	Coarse	100	25
	Grade 1 concrete	Coarse	30	40

landfilling capacity and this, especially in some countries, implies significant impact on the environment (Kien et al. 2013). As a matter of fact, cost-benefit analyses reveal positive results when evaluating CDW recycling solutions and highlight that the landfill charge is a key factor in determining those results and the achievement of a breakeven post after the initial investment (Yaun et al. 2011).

Therefore, any action capable of even slightly reducing both GHG emissions and raw material demand results in a significant global effect on the environment, due to the abovementioned huge figures. In this light, recycling CDW for transforming them into sustainable "second raw materials" is the solution to answer the above requirements and achieve a higher sustainability for the construction industry. Besides the general understanding of recycling solutions for producing "green concrete", quantitative assessment methodologies capable of quantifying and comparing alternative solutions for sustainable concrete are needed for approaching this problem in a rational way. Particularly, the six quantification methodologies listed below can be generally recognised in the studies available in the literature, some of which being also possibly combined in some specific cases (Wu et al. 2014):

- site visit (SV) method, based on direct or indirect surveys carried out at the construction or demolition sites by duly skilled and trained personnel;
- generation rate calculation (GRC) method, intended at determining the waste generation rate for a particular activity unit (i.e. kg/m^2, and m^3/m^2) by means of alternative approaches (such as per capita multiplier, financial value extrapolation and area-based calculation) determined on similar situations analysed in the past;
- lifetime analysis (LA) method, mainly implemented for demolition waste, and based on the principle of material mass balance when turning buildings into demolition rubbles;
- classification system accumulation (CSA) method, based on GRC method with a further classification system providing a tool for determining the contribution of a given material;
- variables modelling (VM) method, consisting in a simulation of the produced amount of CDW taking into account the variables controlling the production of waste, such as economic indicators, construction areas, on-site working conditions;
- other particular methods, such as the assumption of a given percentage of waste generation or other global parameters (the generation of CDW estimated on the amount of annual cement production).

As a proof of concept, the economic viability of building a construction and demolition waste recycling plant in Portugal was analysed by Coelho and de Brito (2013a). According to the analysis proposed in that study, the break-even point is around 2 years and, hence, in spite of the significant initial investment, the construction of this kind of plant can be a profitable investment. Moreover, since the factors affecting this result can be significantly variable even in the short period, a sensitivity analysis was carried out for investigating the influence of various relevant parameters, such as CDW generation rate and landfilling charges and rejected materials. In the worst scenario the return on investment was eight years and, hence, still fairly acceptable (Coelho and de Brito 2013b). A more general “environmental analysis” and the corresponding sensitivity investigation were carried out by the same authors by using primary energy consumption and $CO_{2,eq}$ emission impact factors as environmental impact performance indicators (Coelho and de Brito 2013c, d).